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RESEARCH
REPORT

# Modelling 'leadership-driven' scenarios of the global mitigation effort

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# Summary

This report presents a modelling analysis undertaken by UCL Energy Institute on behalf of the Committee on Climate Change, to explore the UK contribution to the global effort to meet the long-term temperature goal of the Paris Agreement. In particular, it looks at the potential for 'leadership-driven' global transitions and the implications on the global effort of the UK undertaking rapid emission reductions as part of a broader coalition of countries with ambitious climate policy objectives that are in line with the 'common-but-differentiated-responsibility' principle outlined in the Paris Agreement.

To do this, we undertake a scenario modelling approach using the global energy system model, TIAM-UCL, to first consider regional contributions to global emission reductions, including those from the UK, using the typical cost-optimal allocation, for a range of global temperature limits. However, real world experience suggests that this is not necessarily how emission reductions will play out, with many other factors determining action, including the inertia of different sectors within the energy system, governance and national political priorities across a range of individual jurisdictions. In addition, the Paris Agreement requires that developed countries take a lead in cutting emissions with some nations and regions ahead of others in developing climate policy that will enable deeper emission reductions than suggested by these scenarios**.**

A second set of 'leadership-driven' scenarios explores how the UK and partner countries can take stronger and earlier action thereby providing additional emissions "headroom" for other regions, meaning that developing countries have more time to ramp up their mitigation efforts. It also provides the opportunity to drive innovation more rapidly across different technologies, thereby benefitting regions that may be earlier in the transition to a low-carbon economy. Finally, a third set of scenarios explore two critical areas of uncertainty inherent in the modelling – the future evolution of energy demand, and the prospects for afforestation as an alternative to bioenergy with carbon capture and storage (BECCS), as a way of providing negative emissions. Both of these uncertainties are of course linked, as much higher energy demands require higher levels of negative emissions. The purpose of this part of the analysis is therefore to highlight the importance of two of the primary uncertainties that affect the scale of the global challenge to meet the Paris Agreement long-term temperature goal, and to underline the emergence of very different future pathways under the same stringent temperature goals.

The findings of this report reinforces those of other analyses, that all regions need to contribute to the global efforts to reduce emissions of greenhouse gases, if the types of climate objectives set out in the Paris Agreement are to be met. This means global $CO_2$ emissions being net-zero or near-zero by or soon after 2050 if warming is to be kept well-below the 2°C limit, as illustrated by the modelled 1.75°C case. However, given equity and capability considerations under the Paris Agreement, earlier action from developed countries such as the UK could provide some emissions 'headroom' for low carbon transitions in other parts of the world. The analysis shows that this can lead to changes that could help developing countries through the transition to low carbon energy systems, including a lowering of mitigation costs, providing more time to switch away from fossil fuels, and reduced dependency on CCS/BECCS deployment. Crucially, we find that this headroom does not slow the required large-scale deployment of renewable generation technologies, which continue to expand at pace due to their lower cost relative to fossil-based generation going forward.

In those regions taking a leadership role, this would mean a more rapid draw down in the production and use of fossils fuels, the development and use of alternative low carbon fuels, and to some extent, the use of negative emissions for hard-to-mitigate sectors. However, the analysis also

highlights that the higher ambition regions selected only account for 23% of the global $CO_2$ budget share to 2050, meaning that opportunities for budget rebalancing are to some extent limited and that ultimately climate goals can only be met with strengthened action across all regions of the world.

The analysis also underlines the need for an improved representation of other options, including those focused on the industrial and transport sectors, where residual emissions were observed to be highest. This includes both options that can help decarbonise the supply of energy being used in these sectors, additional efficiency gains to reduce the amount of energy required, and demand-side measures that reduce the amount of energy service demand, the impacts of which were illustrated in the modelling of the lower demand scenario. Another key option assessed in this report is large-scale afforestation, which shows strong potential to reduce BECCS dependency, and combined with the lower demand case, highlights how the 1.5°C case can be achieved within globally sustainable bioenergy limits. Both lower demand and afforestation cases require a much stronger focus in future research.

To conclude, if the UK, as part of a group of developed country partners, made efforts to strengthen their climate policies beyond the global least-cost contribution, our modelling indicates that this would provide some headroom for other regions to develop technological solutions more rapidly, including cost reductions through research and innovation, and inform how effective policy packages can be developed. This increase in near term ambition could also help focus the necessary attention on how to tackle those hard-to-mitigate sectors and solutions that have perhaps not been given sufficient attention to date in modelled scenarios, including afforestation and demand-side measures.

# 1. Introduction

This report presents a modelling analysis undertaken by UCL Energy Institute on behalf of the Committee on Climate Change, to explore an effective UK contribution to the global effort to meet the long-term temperature goal of the Paris Agreement. In particular, it looks at the potential for 'leadership-driven' global transitions and the implications on the global effort of the UK undertaking rapid emission reductions as part of a broader coalition of countries.

The CCC is providing advice to the UK Government on whether a change is needed to the UK's long-term domestic climate targets in view of the goals laid out by the Paris Agreement, i.e. limiting global average temperature rise to well below 2°C above pre-industrial levels and pursuing efforts to limit the rise to 1.5°C. It is therefore useful and timely to explore how domestic ambition at the UK level compares to what is needed globally, the impact of increased effort by the UK and other countries pursuing higher levels of ambition, and how increased efforts impact on the necessary efforts by other countries. Such an assessment can help inform how stronger efforts by the UK and partner countries can deliver a balanced, more equitable and practical contribution to global mitigation action, more consistent with the Paris Agreement under which developed countries are expected to take a lead in reducing emissions.

The scale of the global challenge to achieve the long-term temperature goal of the Paris Agreement depends strongly on several elements. Firstly, the extent to which greenhouse gas removals, most notably via bioenergy with carbon capture and storage (BECCS), will feature in the future global energy system. Most scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) see BECCS as critical to achieving long-term climate objectives, yet it has significant socio-economic and technical challenges, and current BECCS deployment levels are insignificant compared to the level of ambition suggested. Secondly, how the energy demand of countries will evolve, which in turn drives the build out of the energy system. The size of the system and resulting emissions will impact the level of required greenhouse gas removals to keep warming to the Paris Agreement long-term temperature goal. Therefore, we explore: i) the potential role of afforestation as an alternative negative emissions option and its interaction with BECCS, and ii) the level of future energy demand as important sensitivities to the picture of the global transition.

# 2. Modelling approach

A modelling approach has been developed to explore the issues outlined above. The methodology employs a global energy system model, TIAM-UCL (detailed in the next section), and first considers regional contributions to global emission reductions, including those from the UK, using the typical cost-optimal allocation, for a range of climate objectives. That is, regions contribute to a global target- based on where emission reductions can be undertaken at the lowest cost.

However, real world experience suggests that this is not necessarily how emission reductions will play out, with many other factors determining action, including the inertia of different sectors within the energy system, governance and national political priorities across a range of individual jurisdictions. In addition, the Paris Agreement requires that developed countries take a lead in cutting emissions with some nations and regions ahead of others in developing climate policy that will enable deeper future emission reductions**.**

The rationale explored here attempts to capture this equity narrative by requiring that developed countries take stronger and earlier action thereby providing additional emissions "headroom" for other regions, meaning that developing countries may have more time to ramp up their mitigation efforts. It also provides the opportunity to drive innovation more rapidly across different technologies, thereby benefitting regions that may be earlier in the transition.

A second set of modelling analysis therefore explores ‘leadership-driven’ global simulations that re-balance action, towards a high ambition coalition (HAC)[1] of countries, including the UK, which make more rapid mitigation efforts than they would otherwise be required to do so under the global ‘least-cost’ simulation. This is more representative of both the emerging reality of where the most ambitious long-term emissions targets are currently being set and is more reflective of the principles of fairness and ‘common-but-differentiated-responsibility’ within the Paris Agreement. The aim of this work is to investigate whether this ‘leadership-driven’ scenario would help facilitate the overall global transition challenge to achieve the Paris Agreement long-term temperature goal. Therefore, the scenarios examined here seek to understand the benefit afforded by developing countries having additional emissions “headroom” so as to provide them with more time to act while at the same time ensuring long-term global climate objectives are achieved.

Finally, a third set of model runs explore two critical areas of uncertainty inherent in the modelling – the future evolution of energy demand, and the prospects for afforestation as an alternative to BECCS, as a way of providing negative emissions. Both of these uncertainties are of course linked, as much higher energy demands require higher levels of negative emissions. The purpose of this analysis is therefore to highlight the importance of two of the primary uncertainties that affect the scale of the global challenge to meet the Paris Agreement long-term temperature goal, and to underline the emergence of very different future pathways under the same stringent climate goals.

## TIAM-UCL

The modelling in this paper has been undertaken using the TIMES Integrated Assessment Model at University College London (TIAM-UCL)[1–3]. This model provides a representation of the global energy system, representing primary energy sources (oil, gas, coal, nuclear, biomass, and renewables) from production through to their conversion (e.g. electricity production), their transport and distribution, and their eventual use to meet energy demands across a range of economic sectors. Using a scenario-based approach, the evolution of the system to meet future energy service demands (including mobility, lighting, residential and industrial heat and cooling), can be simulated, driven by a least-cost objective. Future energy service demands are dynamic, in that they can rise or fall in response to changes in the cost of providing energy services via the use of long run price elasticities. Therefore, reductions of energy service demands also become a mechanism for reducing emissions. The least cost objective is to minimise the discounted total system cost over the full time horizon of the model, based on a discount factor of 3.5%.

The model splits the globe up into 16 regions, including the UK as one of them, which allows for a detailed characterisation of regional energy sectors, and the trade flows between them. Future demands for energy services, which increase due to population and economic growth, drive the evolution of the energy system that must meet these demand requirements. Decisions around what energy sector investments to make across regions to meet these demands are determined on the basis of the most cost-effective investments, taking into account the existing system in 2015, energy resource potential, technology availability, and crucially policy constraints such as emissions reduction targets. The model time horizon runs to 2100, in line with the timescale typically used in these simulations. The model does have the ability to remove emissions from the atmosphere via negative emissions, based on a set of BECCS technologies (in power generation, industry, and in $H_2$

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[1] This high ambition coalition is not intended to exactly represent the grouping that has emerged from recent climate conferences https://ec.europa.eu/clima/sites/clima/files/news/20181211_statement_en.pdf

and biofuel production). The primary limiting factor on this technology is the global bioenergy resource potential, set at a maximum 110 EJ per year, in line with recent CCC biomass report[4]. This is a lower level than the biomass resource available in many other integrated assessment scenarios (which can be up to 300 EJ/yr) and is more representative of an upper estimate of the global resource of truly low-carbon sustainable biomass by many ‘ecological-based’ studies[5].

A climate module is also integrated into the model framework, calibrated to the MAGICC simple climate model used by the IPCC[6], allowing for a simplified representation of the climate system. It ensures that any future energy system is consistent with a given temperature objective, such as limiting warming to 1.5°C or 2°C by 2100 and beyond. To this end, the climate module is run out well beyond 2100 to ensure emission levels in 2100, and the underlying energy system, are consistent with maintaining a stable temperature from that point onwards. As described later, this approach is coupled with carbon budgets in order to be more representative of the most up-to-date climate science assessed by the IPCC that used multiple lines of evidence to estimate carbon budgets and not just simple climate models.

For $CH_4$ and $N_2O$ emission levels, non-energy sector related emissions (outside of the energy system) are fixed based on RCP2.6 trajectory. This sees non-$CO_2$ emissions decline rapidly (particularly for methane emissions) over the next few decades and, when coupled with sufficiently rapid reductions in $CO_2$ emissions, would be approximately consistent with keeping median expected peak warming around 1.5◦C. However, emissions of non-$CO_2$ GHGs from the energy system are endogenously modelled, with mitigation options available, for example, to reduce $CH_4$ leakage from oil and gas extraction and supply activities. This allows the model to replicate the crucial role of increasing the stringency of environmental regulation for oil and gas systems. The sum of the exogenous and endogenous emissions are required (via a constraint) to be below a declining emission trajectory out to 2100. For $CH_4$ and $N_2O$ these constraints are derived separately and are based on the mean of pathways used in the IPCC Special Report on 1.5°C (here after SR1.5) that meet a 2°C climate target in 2100[7] (noting that this includes scenarios from the SR1.5 database that achieve close (+/- 0.1°C) to the 2°C target in 2100..

The model also has a backstop mechanism, meaning that if it does not have sufficient mitigation options to remain within a given carbon budgets or temperature limit, it can deploy this mechanism. However, it only does so as a last resort, as the option is costed well above the highest cost technological option in the model, at £5000/$tCO_2$. The purpose of this backstop mechanism is not to represent a unicorn technology, but rather to allow the model to solve so that other insights can be gained e.g. which sectors have highest residual emissions? To what extent is the carbon budget exceeded? Its use in this context can be found in Winning et al. (2018).[8]

Core assumptions used in the model are provided in Appendix 1.

## Scenario definition

To meet the research objectives of our analysis, three sets of scenarios have been constructed to help explore how emissions can be reduced, including the UK’s contribution, to achieve the climate policy goals set out in the Paris Agreement[9].

A first set of scenarios, using Shared Socio-economic Pathway 2 (SSP2) derived energy service demands[10], focus on the implications of different climate targets, with regional contribution to mitigation determined based on the most economically optimal distribution. Labelled ‘global least-cost’, four levels of climate ambition have been modelled (Table 1), including 2°C, 1.75°C and 1.5°C temperature targets at 66% probability, and 1.5°C at 50% probability. The main CCC advice report interpreted the Paris Agreement long-term temperature goal as having a level of ambition bounded by at least 66% 2°C scenarios at the minimum ambition end. Therefore, we focus on 66% 1.75°C warming scenario as indicative of the middle of the range 'well-below' 2°C case. The 800 $GtCO_2$ carbon budget associated with this level of ambition is representative of IAM scenarios in SR1.5 that keep warming below 2◦C (>66%) when budgets are calculated to the time of net-zero $CO_2$ emissions[11].

Differing levels of climate ambition are modelled by implementing a range of global carbon budgets within the model, the assumptions for which are based on the latest science, and taken from the IPCC SR1.5 report, Table 2.2[12]. The climate module is also used to ensure that warming does not exceed 2°C under any scenario, and that temperature targets are hit in 2100. Overshoot in the 1.5°C and 1.75°C cases is permitted due to the inability of the model to remain below these limits due to a combination of a warming in 2005 of 0.86°C (taken from Table 1.1 of the SR1.5 report) and strong energy demand growth in the near term.

**Table 1. Global least-cost scenarios.** 'GCB' refers to the global carbon budget, from 2018 onwards

| No. | Scenario | GCB, $GtCO_2$* | Peak warming year** | Warming limit | Additional description |
|---|---|---|---|---|---|
| 1 | 2C (66) | 1170 | 2060 | 2°C (66%) | |
| 2 | 1.75C (66) | 800 | 2055 | 1.75°C (66%) | |
| 3 | 1.5C (50) | 580 | 2050 | 1.5°C (50%) | |
| 4 | 1.5C (66) | 420 | 2050 | 1.5°C (66%) | |

* Unless stated, the global carbon budget refers to the cumulative remaining $CO_2$ emissions, from 2018 onwards.
** Note that these are an output of the model, and not imposed as constraints as per the other assumptions listed.

A further set of scenarios simulate a 'leadership-driven' approach in which the UK and other partner countries push for stronger levels of ambition prior to 2050 than found in the global 'least-cost' simulation (see Table 2). The group of countries with a stronger level of ambition (relative to the 'global least-cost' scenarios) is based on the Higher Ambition Coalition[2], but also includes other developed countries that are currently showing potential for setting ambitious climate targets, or are key global players that have strong responsibility for past climate change and/or capability to reduce emissions, such as the USA and Australia.

The rebalancing involves all HAC countries having to reach at least net-zero $CO_2$ emissions by 2050, as being considered by a number of regions and countries around the world, such as the European Union[13].[3] A set of sensitivities is then run which incrementally reduces the HAC group 2018-2050 carbon budget in 10% increments to a 50% reduction (halving of the budget), relative to the global least-cost scenario. The overall global carbon budget remains the same, so non-HAC countries share the extra budget previously used by the HAC group, as determined by the model.

The rebalanced cases are run for two ambition levels, the 2.0°C and 1.75°C cases (both at 66% probability), but not the 1. 5°C cases. For the latter cases, their omission is because the model finds that there is effectively no opportunity for rebalancing. All regions are deploying mitigation options at a near maximum level, pushing as hard and rapidly as possible towards net-zero $CO_2$ emissions by

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[2] Countries included in the grouping for the modelling undertaken in this report includes Europe, USA, Japan, South Korea, UK, Canada, Australia and Mexico.

[3] Under the least-cost global scenario, $CO_2$ emissions, while near zero, are not net-zero for most developed countries until after 2050.

2050. Therefore, headroom for specific regions to adopt slower mitigation rates is not feasible at this level of climate ambition.

A further scenario has also been run, using an alternative HAC grouping ('HAC-CHI'), with the membership changed by including China and excluding the USA. This is reflective of a situation whereby China takes up the climate leadership mantle currently vacated by the USA. This has been run for the 2°C (66%) case.

**Table 2. Rebalanced high ambition coalition scenarios.** 'GCB' refers to the remaining global carbon budget, from 2018 onwards. Note that all regions in the HAC group also reach net-zero $CO_2$ emissions in 2050.

| **No** | **Scenario** | **GCB, $GtCO_2$** | **Peak warming year** | **Warming limit, 2100** | **Additional description** |
|---|---|---|---|---|---|
| 1 | 1.75C(66) HAC | 800 | 2055 | 1.75°C (66%) | The 50% HAC budget reduction cases only solves with the backstop |
| 2 | 2C(66) HAC | 1170 | 2060 | 2°C (66%) | |
| 3 | 2C (66) HAC-CHI | 1170 | 2060 | 2°C (66%) | All cases rely on the backstop. The 10-30% cases exceed the budget by 2.5 Gt prior to 2050; for CB40-50, the exceedance is much higher. |

Finally, Table 3 lists the third set of scenarios, which explore the critical uncertainties related to the role of afforestation and BECCS, and the future levels of energy demand. The afforestation scenario is motivated by an interest in the potential role of this option as an alternative strategy to large-scale BECCS, with its arguably lower risk supply chains, and multiple co-benefits[14]. The lower demand scenario[15], based on SSP1 GDP and population assumptions[4], reflects the large uncertainty in the demand projections used in TIAM-UCL, and prospects for demand-side action that could again reduce dependency on BECCS. The two sensitivities modelled together also allow for insights from exploring the feasibility of deep emission reductions to keep warming to 1.5°C.

Further information on the set-up of these afforestation and demand scenarios can be found in Appendix 2.

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[4] This 'sustainability' based narrative reflects stronger demographic transition due to education and health, leading to a lower global population. Economic growth is modestly increased, with a focus placed on environmentally benign technologies and energy efficiency. In SSP1, the global population rises to 6.9 bn people in 2100, compared to 9.0 bn in SSP2; in SSP1, global GDP rises to $566 tn by 2100, compared with $539 tn in SSP2.

**Table 3. Afforestation and energy demand level sensitivities.** 'GCB' refers to remaining global carbon budget, from 2018 onwards.

| No | Scenario | GCB, $GtCO_2$ | Peak warming | Peak warming year(s) | Warming limit, 2100 | Additional description |
|---|---|---|---|---|---|---|
| 1 | 2C (66) Aff | 1170 | 2°C | 2060 | 2°C (66%) | The land used for growing energy crops is instead used entirely for afforestation. |
| 2 | 1.5C (66) Aff | 420 | 1.86°C | 2050 | 1.5°C (66%) | |
| 3 | 2C (66) LoDem | 1170 | 2°C | 2060 | 2°C (66%) | Scenarios use SSP1 derived energy service demand projections, which are lower than SSP2. |
| 4 | 1.5C (66) LoDem | 420 | 1.87°C | 2050 | 1.5°C (66%) | |
| 5 | 2C (66) LoDem-Aff | 1170 | 2°C | 2060 | 2°C (66%) | Scenarios combine afforestation and lower demand cases. |
| 6 | 1.5C (66) LoDem-Aff | 420 | 1.89°C | 2050 | 1.5°C (66%) | |

The results of the three sets of scenarios are presented below. We start with the global least-cost scenarios that have been run to determine the model's cost-effective allocations of emission reductions to different parts of the world. We then move to the 'leadership-driven' scenarios, 'rebalancing' the global effort across regions, to explore the role of stronger earlier action by UK and partners in a high ambition coalition. Finally, we explore the critical uncertainties inherent in the scenarios undertaken, focusing on prospects for negative emission options and different demand projections.

# 3. Global least-cost scenarios

**Key results**

- The 1.75°C scenario, with a carbon budget of 800 $GtCO_2$, see near-zero $CO_2$ emissions (~3 $GtCO_2$) by 2060 and net-zero $CO_2$ emissions by the end of the century.
- Key features of this transition include large-scale deployment of renewables, driving a more than 4 fold increase in generation for electrification of energy services by 2050, including for mobility and heating. CCS also plays a role, with a cumulative total of 535 $GtCO_2$ sequestered, almost half of which is BECCS. Bioenergy use doubles, while coal use is at 10% of 2015 levels in 2050.
- Under all ambition cases, the global deployment of renewables is pushed to maximum potential (in the model), reflecting the cost-competitiveness and large potential for such technologies, and the external costs of fossil-based sources.
- Higher ambition cases show an increasing reliance on BECCS for negative emissions. Whilst this highlights that some negative emissions are likely needed for hard-to-treat sectors, it also suggests much more thinking is required on options to reduce emissions in the near term, particularly on the demand-side, to limit exposure to the substantial risks associated with significant BECCS dependency.
- Emission pathways compatible with the 1.5°C target have not been produced in this modelling (except with the deployment of a 'backstop' technology). Compared to other published 1.5°C scenarios, this is due to an assumed lower global biomass potential (within sustainability limits), lower CCS deployment rates, and higher residual emissions in industry and transport.
- In this global least-cost set-up the model simulates a UK contribution, under a 1.75°C target, of net-zero $CO_2$ emissions by 2065, although emissions are near-zero in 2050.

## Emission reductions

The $CO_2$ emission trajectories from the global least-cost scenarios are shown in Figure 1, compared to the 1.5°C scenario set from the SR1.5 database (grey-pink trajectories), and the 'Lower 2C' case, approximately equivalent to the 1.75°C climate policy case used in this analysis. It is worth noting that in cumulative emission terms, the 1.5°C scenarios run here are higher than those in the SR1.5 database. For example the 1.5C(66) case is at the upper end of the interquartile range (at 500 $GtCO_2$ from 2016[5]), while all the other three scenarios are above this range.

In both 1.5C(50) and 1.5C(66) scenarios, represented by the red trajectories, the model did not solve without a 'backstop' technology.[6] This means that these pathways were not found to be compatible with the target, with budget exceedances of 218 $GtCO_2$ and of 271 $GtCO_2$ respectively (or annual

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[5] The 1.5C (66) budget of 420 $GtCO_2$ (from 2018 onwards) has been adjusted in these plots to account for 2016 and 2017, to ensure comparability with results in the SR1.5 database.

[6] This is determined by the uptake of a so-called 'backstop' technology. This is a technology costed at $ 5000/$tCO_2$ that only appears in the absence of any other mitigation technology.

exceedances of 6-8 GtCO$_2$ per annum during the period 2070-2090). In the emission trajectories shown, these pathways include the backstop technology that compensates for the budget exceedance, to provide a representation of necessary reductions under such climate targets. The budget exceedance in the 1.5C(66) case is equivalent to two-thirds of its 420 GtCO$_2$ carbon budget. The exceedance is due to the modelled rate of mitigation being insufficient to bring emissions to net zero or below rapidly enough, leaving residual emissions across specific sectors, and modelled post-2050 greenhouse gas removal (GGR) measures not at a level that can sufficiently draw down emissions by 2100. This reflects a restriction on the bioenergy resource, based on the CCC view of sustainable levels, and constrained rollout of CCS (to allow for BECCS).

As a result, these scenarios avoid the significant risks of relying on the socio-economically challenging large scale deployment of as yet unproven technologies later in the century for CO$_2$ removal – but requires the use of a backstop technology to stay within the required cumulative carbon budget. This highlights the scale of the challenge and reinforces the need to explore further action across other sectors, either constrained or not included in the model, focusing on existing reductions options that can be deployed today or in the near term, and potentially other negative emission technologies e.g. Direct Air Capture of CO$_2$.

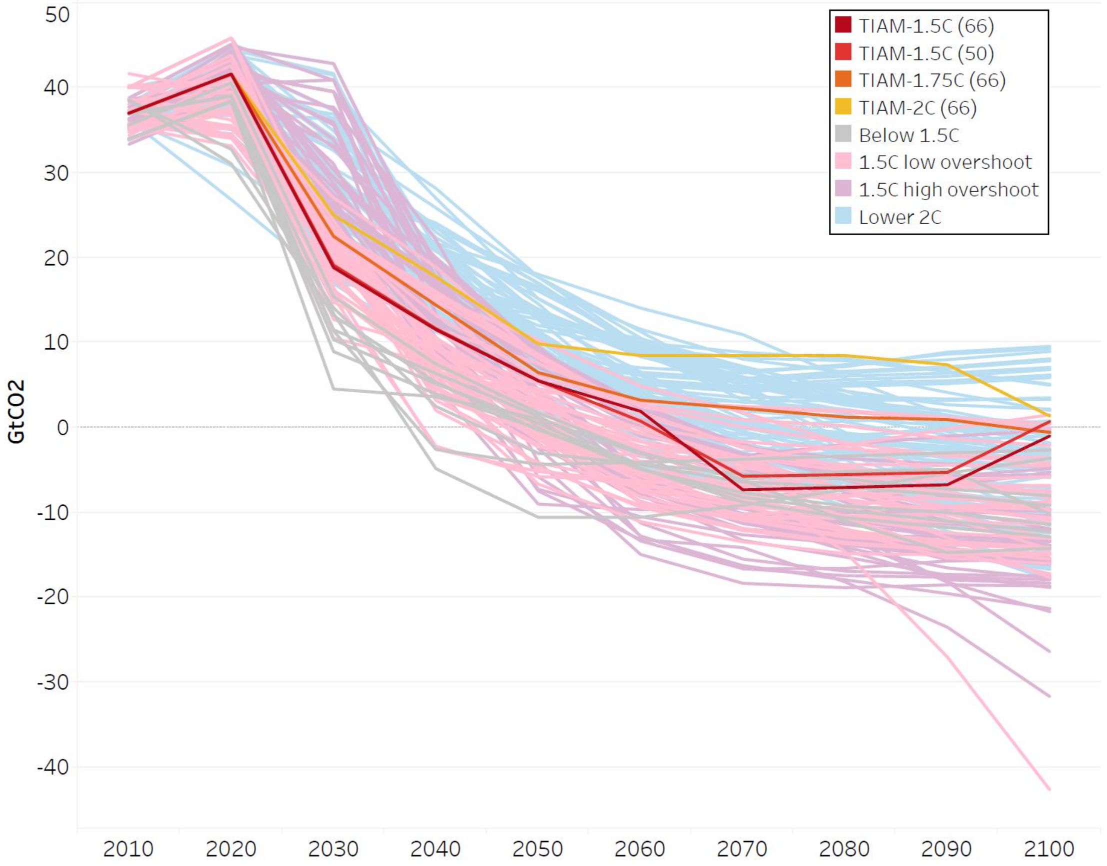

**Figure 1. TIAM-UCL CO$_2$ trajectories compared to 1.5°C scenarios in SR1.5 database.** Trend lines in bold represent TIAM-UCL scenarios; other scenarios for comparison represent different categories according to global warming impact.

In the 1.75(66) case, CO$_2$ emissions fall to around 6 GtCO$_2$ by 2050, 3 GtCO$_2$ by 2060 (relatively close to net-zero at this point), with a gradual decline down to net-zero just before 2100.[7] Global GHG emissions do not go to net-zero, and are around 5Gt CO$_2$e by 2100. A total of 535 GtCO$_2$ cumulative sequestration is also deployed, almost half of which is BECCS. By 2100, annual sequestration via

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[7] This run sees an 11 Gt CO$_2$ exceedance in emission in the late 2090s (out of a cumulative budget of 800 Gt). Given the uncertainty in this last period, this scenario has been fully considered in the results.

BECCS is 3.7 $GtCO_2$. This means that while the global carbon budget is 800 $GtCO_2$, the model has a further 500 $GtCO_2$ of additional gross (positive) emissions budget provided by CCS.

In the 2C(66) case, $CO_2$ emissions decline to 10 Gt by 2050, and down to around 1 Gt by 2100, so at the global level are not net-zero. This case sequesters a higher level of cumulative $CO_2$ (555 Gt) than observed under the 1.75(66), but with a lower level of BECCS (200 Gt). This reflects a reduced need to remove $CO_2$ from the atmosphere via negative emissions given the larger budget.

As shown in Figure 2 below, both of these cases see a strong decline to 2050, with substantial action in the decades after 2020 e.g. a more than halving of $CO_2$ emissions in regions such as China and the USA. This means global mitigation rates of 6% and 4.7% per annum between 2020 and 2050 in the 1.75°C and 2°C cases respectively. A large part of this reduction is the effective collapse in the use of coal in power generation, and massive ramping up of alternative low-carbon capacity, largely renewables. While recent trends suggest strong inertia in the system to effect such a change[16], the modelling provides useful insights into the required action. It also highlights the more aggressive global action required under the 1.5°C cases, particularly over the next decade.[8] Post-2050, a key difference between the two cases is the higher emissions in 2C(66), due to the much larger carbon budget.

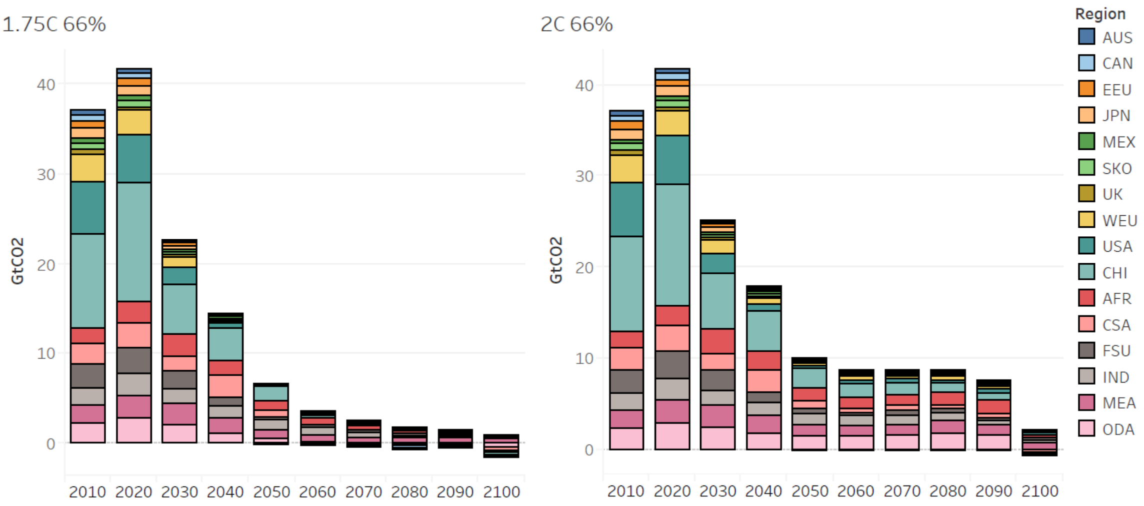

**Figure 2. $CO_2$ emission levels by region for selected scenarios, 2010-2100**

For the UK, the trajectories observed under the three budget cases are not dissimilar to those published in Pye et al. 2017, a UK-based modelling analysis exploring net-zero $CO_2$ energy systems[17]. The scenario information for the UK based on the modelling are summarised in the table below. To reiterate, these are the outcome of a global least-cost allocation of emission reductions.

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[8] Other scenarios see a different outlook, with less ambitious mitigation in the pre-2050 period, and more ambitious scaling of GGR options in the second half of the century.

**Table 4. Characteristics of the UK low carbon pathway in 1.75C(66) and 2C(66) global least-cost scenarios.**

| Scenario | Budget 2018-2050, $GtCO_2$ | Budget 2018-2100***, $GtCO_2$ | Global budget share, 2018-2100 | Net-zero $CO_2$ year* | $CO_2$ emission reduction by 2050** | GHG emission reduction by 2050** | CCS contribution, $GtCO_2$ (BECCS share), 2018-2100 |
|---|---|---|---|---|---|---|---|
| 1.75C(66) | 5.4 | 5.1 | 0.6% | 2065 | 98% | 93% | 6.3 (84%) |
| 2C(66) | 7.1 | 11.6 | 1.0% | - | 86% | 84% | 1.9 (49%) |

* This is the year at which the $CO_2$ emissions on a net basis (sources net of sinks) are at zero or less.
** Relative to 1990 levels. Percentage reductions greater than 100% indicate negative emissions.
*** Note that this budget is also for all years from now onwards (beyond 2100). The climate module therefore ensures that emissions are at a level in 2100 consistent with not exceeding a specific level of warming beyond 2100.

Net-zero $CO_2$ emissions occurs by 2065 under 1.75C(66). Given the size of the carbon budget in 2C(66), emissions remain above zero, at 55 $MtCO_2$ in 2100. In the scenario on which we focus - 1.75C(66) - a mitigation rate of almost 10% year-on-year, in the period to 2050. This is much higher than the rate needed to achieve the 4th and 5th carbon budgets. As shown in Table 4, CCS plays an important role, providing a higher level of $CO_2$ sequestration (6.3 $GtCO_2$) than the stated carbon budget over the same period (5.1 $GtCO_2$), under 1.75C(66). It is also worth noting the share of capture via BECCS versus other CCS pathways, which are higher under increased stringency due to the increasing need to offset emissions later in the century.

## The challenge of meeting 1.5C

In both 1.5°C scenarios, while we observe budget exceedances, the results can still provide useful insights. First, we can better understand the sources of residual emissions that are challenging for the model to mitigate. Second, we can contrast these scenario with those in the SR1.5 database, to understand why some 1.5°C scenarios are achieved while those in this analysis are not. This avoids the approach of changing assumptions to meet the target, but rather accepting the model is constrained and understanding why.

A comparison of the scenarios undertaken in this modelling exercise with scenarios in the SR1.5 database highlights some key differences. A first constraining factor in TIAM-UCL relative to other SR1.5 scenarios is the level of CCS deployment. The $CO_2$ budget levels for the TIAM-UCL cases are shown below in Figure 3, alongside the 1.5°C compliant SR1.5 scenarios, and compared against cumulative capture of $CO_2$. We find that cumulative CCS is in the region of 500-600 $GtCO_2$ across all scenarios due to assumed growth constraints, and therefore lower than the majority of 1.5°C scenarios in the SR1.5. The same is true for the subset of BECCS, where TIAM-UCL estimates are no higher than 250 Gt. A key constraining factor on the BECCS level is the bioenergy availability, while for CCS, residual emissions (resulting from the capture efficiency) limit deployment.

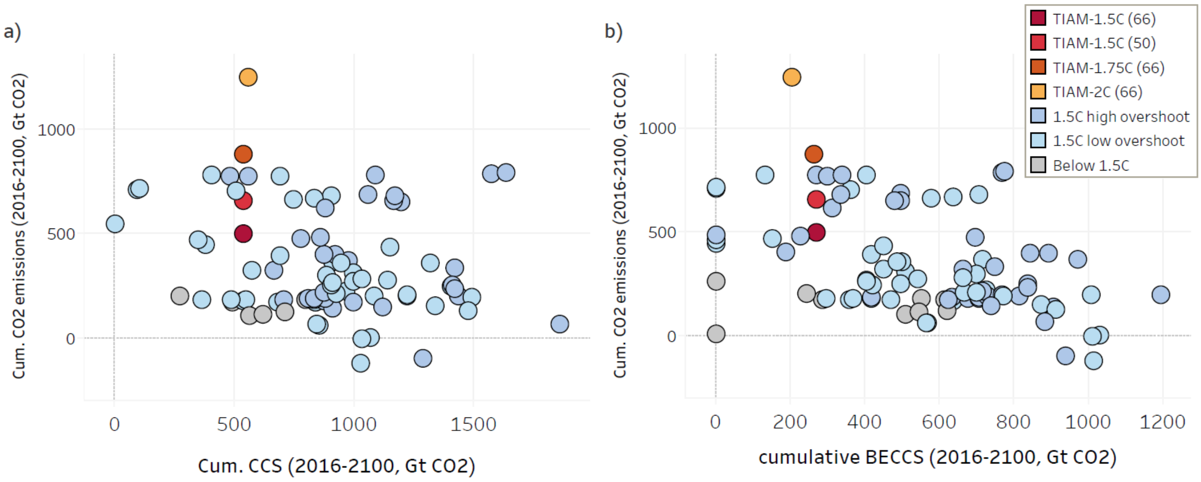

**Figure 3. TIAM-UCL cumulative $CO_2$ capture total and for BECCS only versus global $CO_2$ budget level compared to 1.5°C scenarios in SR1.5 database.**

As with CCS, the maximum resource level of bioenergy is much lower than most other high ambition scenarios in the SR1.5 database. Bioenergy use to 2100, shown in Figure 4, sees levels peaking at around 110 EJ, compared to the median value of 230 EJ in the SR1.5 ensemble. This is in line with the view taken by the CCC regarding sustainable global levels of bioenergy, as per their recent assessment[4].

A third factor are the residual emissions, those sources that have few mitigation options (in reality or modelled) to allow for fuller decarbonisation. From 2070 onwards, industrial sector emissions stubbornly remain at around 2 $GtCO_2$ out to 2100. While the sector is undertaking significant mitigation efforts, the rate of industry sector growth means absolute emissions do not decline at the same rate. The comparison with 1.5°C scenarios in the SR1.5 database shows that TIAM-UCL is at the upper end of the range. Further work is needed to explore near term growth of emissions, future growth of different sectors, and the full range of emission abatement options required. The other key sector with residual emissions is transport, where we observe a floor of around 2 $GtCO_2$ from 2050 onwards which predominately originating from aviation due to the significant technical challenges around deep decarbonisation of this mode.

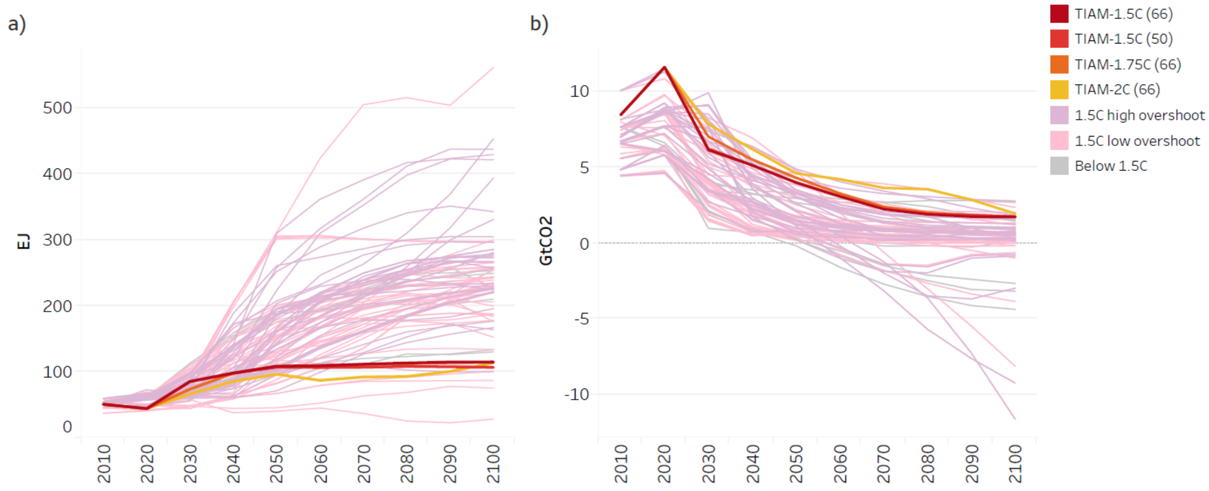

**Figure 4. TIAM-UCL primary bioenergy production (a) and industry sector $CO_2$ emissions (b) compared to 1.5°C scenarios in SR1.5 database**

## Renewable deployment

A clear insight from the global least-cost TIAM-UCL scenarios is that the future deployment of renewables does not vary between scenarios. On a cost-competitive basis, these technologies are shown to consistently be the dominant form of electricity generation in the long term. This implies that under any climate target the rapid and large-scale deployment of renewable low carbon generation is essential, and that the determining factor of the eventual climate ambition achieved with be the extent of reduction in other sectors, alongside power sector decarbonisation.

Different categories of low carbon generation in TIAM-UCL are shown in Figure 5, and again compared to the SR1.5 dataset. All of the TIAM-UCL scenarios are in the range of SR1.5 scenarios, although there are clearly more optimistic outlooks for solar technologies (than assumed in TIAM-UCL). Solar PV is an interesting case with the TIAM-UCL estimates at the top end of one cluster – but then another cluster that is much higher (in the 60-100 TW range by 2100, mainly based on the REMIND model). This upper range appears extremely optimistic compared to historical build rates, implying annual additions of over 1200 GW/yr compared to ~100 GW/yr in the recent past. Both wind and overall electricity generation in TIAM-UCL are at the upper end of the scenario ensemble.

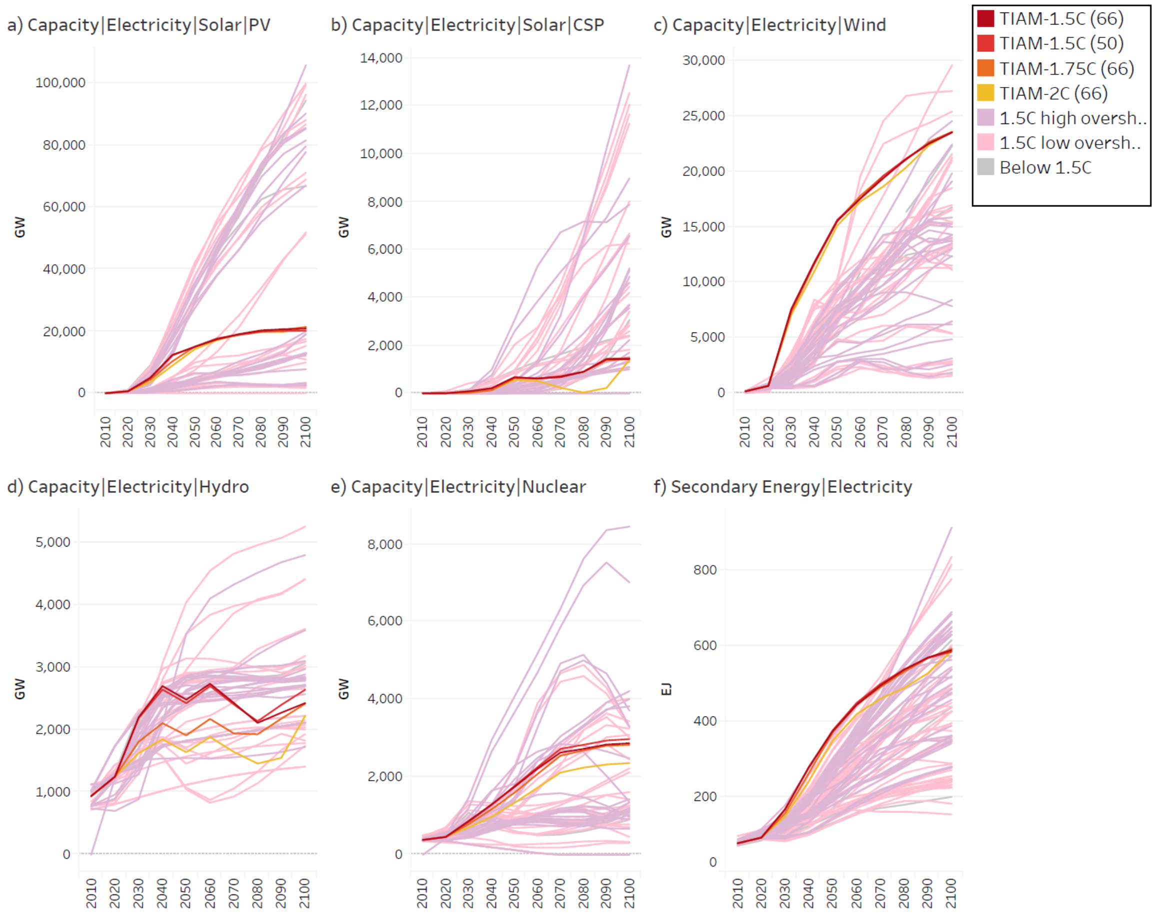

**Figure 5. TIAM-UCL power generation capacities by technology (a-e) and total generation (f) compared to scenarios in SR1.5 database**

# 4. Leadership-driven scenarios

**Key results**

- The 'leadership-driven' scenarios show that there are opportunities for developed countries to strengthen their ambition and take a larger share of the global mitigation effort than in the global least-cost scenarios. This provides some additional emissions 'headroom' for low carbon transitions in other parts of the world. However, at the global level, with only 23% of the global $CO_2$ budget share to 2050 under the global least-cost case, there are constraints on the extent to which the budget can be rebalanced by additional effort across a group of developed countries setting ambitious mitigation goals.

- Under 1.75°C and 2°C scenarios, the pre-2050 $CO_2$ budget share of the HAC regions can be reduced by up to 40% and 50% respectively without creating a need for the model's backstop. Under the 1.75°C case, a 50% reduction for the HAC regions leads to the use of the backstop in the modelled scenarios.

- The year at which the High Ambition Coalition (HAC) grouping achieves net-zero $CO_2$ and GHG emissions moves closer to the present as the coalition's budget tightens. For instance, the 1.75°C scenario sees a shift from 2050 to 2035-2040 for net-zero $CO_2$, while net-zero GHGs are achieved by 2045.

- Reallocation of the global $CO_2$ budget significantly alters the high level energy system evolution for non-HAC regions by: lowering mitigation costs, providing more time to switch away from fossil fuels, and leads to less dependency on CCS/BECCS deployment. Crucially, there is no impact on renewable generation, which remain at levels observed under the optimal case, and do not reduce.

- Contemporaneously, HAC regions see a faster transition away from fossil fuel production, more rapid growth of low carbon energy vectors like electricity and hydrogen, faster CCS and BECCS deployment (including increased biomass imports) and a higher, more equitable share of the cost of achieving global climate objectives.

- Within the HAC grouping, the UK achieves net-zero GHG emissions by 2050 at the latest for all HAC carbon budgets tighter than the base HAC scenario, i.e. 10% reductions and beyond. The scale of net negative $CO_2$ emissions grows as budget stringency increases, reaching at most 200 $MtCO_2$ captured per year.

- To achieve this, these modelled pathways require the UK to deploy CCS faster and to achieve a more rapid removal of oil and uptake of low carbon energy vectors in the transport sector as the HAC budget reduces. However, the rapidity of electrification, wind deployment and the phase out of unabated fossil electricity generation is consistent for the UK across all HAC scenarios.

## HAC to Non-HAC Rebalancing: The Global Picture

The so-called 'leadership-driven' scenarios explore how a coalition of countries taking stronger action before 2050 could provide additional emissions 'headroom' for other parts of the world, while at the same time benefiting from this earlier action in terms of technological innovation, cost reduction and the opportunity for their home-grown, industries to provide for the global low carbon transition. The way that this is modelled is simply to simulate this effect of earlier action, and should not be interpreted as a policy mechanism through which to redistribute effort.

We model the additional effort of the high ambition coalition, or HAC group, by requiring that these countries reach net zero $CO_2$ emissions by 2050 at the latest and by reducing the cumulative carbon budget across the coalition in the period to 2050, under both 1.75°C and 2°C targets (scenario names suffixed 'HAC' e.g. '1.75C (66) HAC') from the global least-cost allocation. The budget reductions considered a range from 10% up to 50%, equivalent to a halving of the 2018-2050 budget in these regions under the modelled global least-cost scenario. A further scenario explores a different HAC membership under the 2°C target, to include China but not the USA ('2C (66) HAC-CHI'). As with the global least-cost scenarios, these scenarios also use SSP2-derived energy service demand projections.

The same assessment has not been undertaken for the 1.5°C cases, given the budget exceedance described in section 3 for the global least-cost scenario, and given such a scenario does not anyway allow for budget rebalancing, with all regions deploying maximum mitigation, and hitting net-zero $CO_2$ by 2050 or soon after.

The differences in the 2018-2050 cumulative $CO_2$ budgets are shown below in Figure 6, where the orange and blue bars represent the HAC and non-HAC group countries respectively. A first observation is that the budget share for the HAC regions is 22% and 23% in 1.75C(66) and 2C(66) respectively, prior to rebalancing, for the 2018-2050 period.[9] This relatively small budget share, compared to the non-HAC group, as most of the emissions growth to 2050 is expected in developing regions. This means that the impact of any rebalancing is constrained by what can be reallocated from the HAC region, which is much smaller in terms of resulting cumulative emissions.

In the 'HAC-CHI' variant (not shown), the HAC group budget is much larger due to the introduction of China. The inclusion of China in the HAC group (and omission of the USA) sees the HAC group budget share under a 2°C case increase to 41%. However, this case is not presented in detail here as the model requires backstop mitigation of 500 $MtCO_2$ for the China region in 2050, the point at which it has to be net zero. This implies a very large-scale challenge of stronger reductions for China than its share in the global least-cost simulation, given its current level of emissions, and the rate of mitigation permitted in the model.

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[9] Note that this HAC grouping accounted for 33% of global $CO_2$ emissions in 2015.

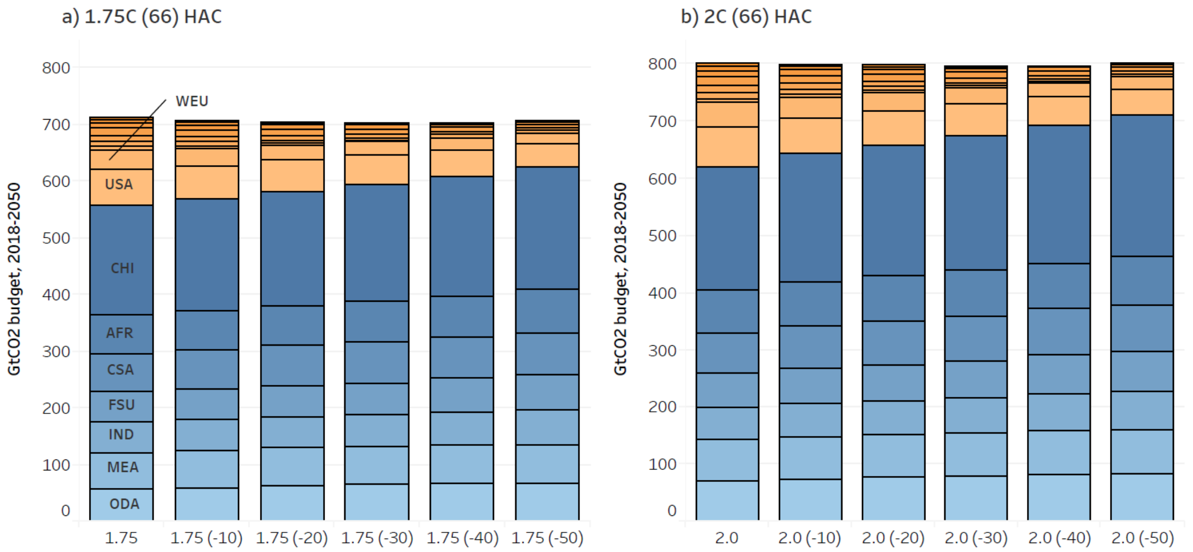

**Figure 6. Budget shares by region for 2018-2050 under the 'leadership-driven' scenarios.** a) 1.75C target and b) 2C target level. On the horizontal axis, the bracketed values represent the % reduction in HAC group budget, relative to the left hand column representing the least-cost case. Note that aggregated budget level for the aggregate HAC group is an input to the model, but the budget level at the regional level is determined by the model subject to the above constraint.

The increased budget allocation to the non-HAC group does not lead to marked changes in the percentage shares of group budget across the non-HAC regions, implying that the relative allocation made by the model is uniform (Figure 7c and d). For the HAC group, the main beneficiary in relative terms is the USA, whose relative contribution to the non-HAC group reduces as the HAC budget reduces; the USA budget share prior to reductions is 41%, but this increases to 51% under the 1.75C(66) -40% case. A similar trend is observed for 2C(66) HAC case (Figure 7a and b).

However, in absolute terms it is the USA that reduces its cumulative $CO_2$ emissions the most due to the need to mitigate more by the HAC group overall and its dominant share of HAC emissions. The western Europe's budget share increases from 22% to 24% under the 1.75C(66) -40% case. All other regions see a decrease in budget share with the UK reducing from 3% to less than 1% of the HAC grouping's allocation. More work needs to be undertaken to better understand the underlying reasons for different relative shares, but it is likely to be due to cost differences between regions, and reasons for allowing more flexibility in certain regions e.g. due to specific industry production profiles.

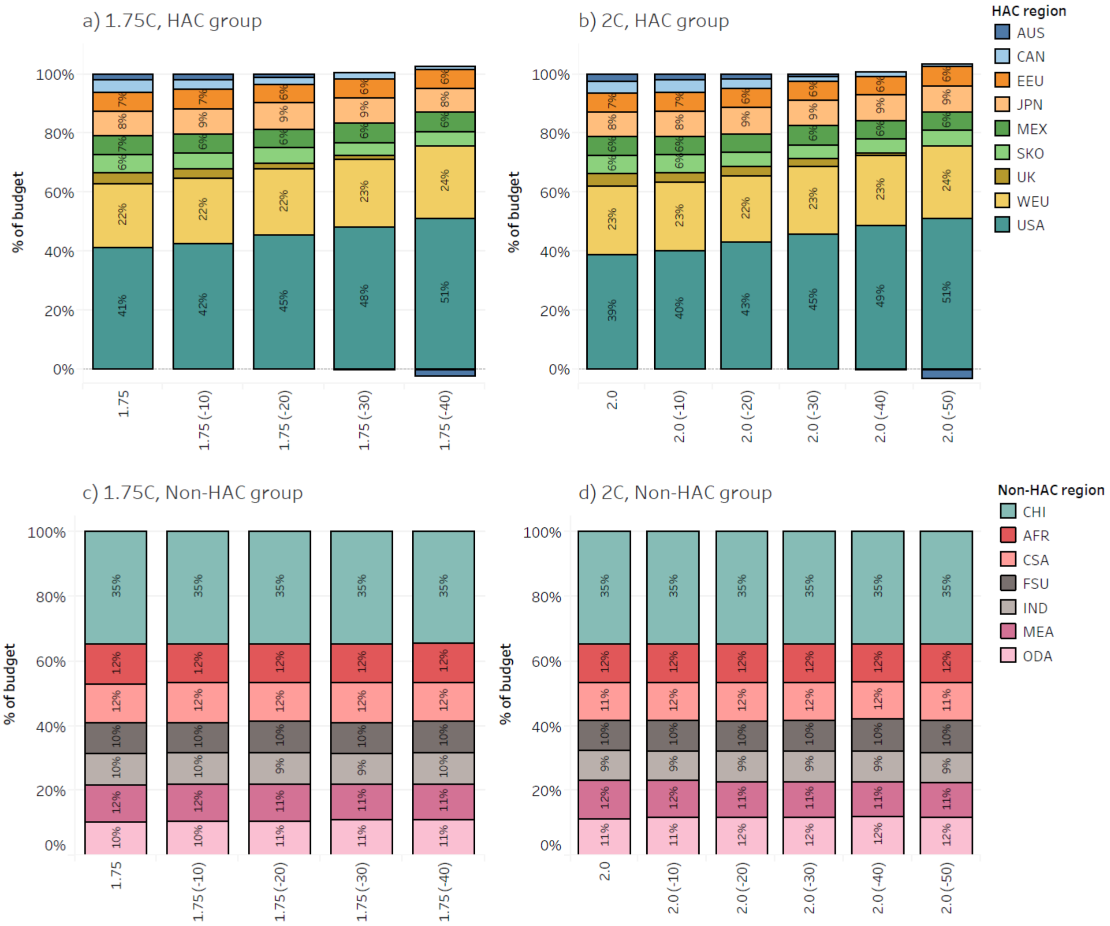

**Figure 7. Share of HAC and non-HAC group budget levels by region for 2018-2050 under the 'leadership- driven' scenarios.** The 1.75C (-50%) case has been omitted from the figure as this scenario did not solve without budget exceedances.

The resulting emission trajectories of the aggregated HAC and non-HAC coalitions based on the leadership-driven approach are shown in Figure 8. The HAC group see a proportionately larger shift, with changes less dramatic (although not insignificant) for non-HAC regions given their larger budgets (prior to rebalancing). For the 1.75C(66) HAC case, only the 50% reduction case is omitted due to the exceedance of the $CO_2$ budget i.e. the backstop is found in the model solution; under the 2C(66) HAC case, all cases are included.

As would be expected, the non-HAC group sees reduced mitigation rates. In the 1.75C HAC case (Figure 8c), the annual mitigation rate to 2050 drops from 5% to 4.7% and 3.9% in the 10% and 40% reduction cases respectively.  In the 2C HAC case, it reduces from 3.9% to 3.5% and 2.8% in the 10% and 50% cases (Figure 8d). Conversely, the HAC group sees increasing mitigation rates, hitting net-zero $CO_2$ emissions by 2040 under the highest budget reduction cases in both the 1.75C and 2C cases (Figure 8a and Figure 8b).

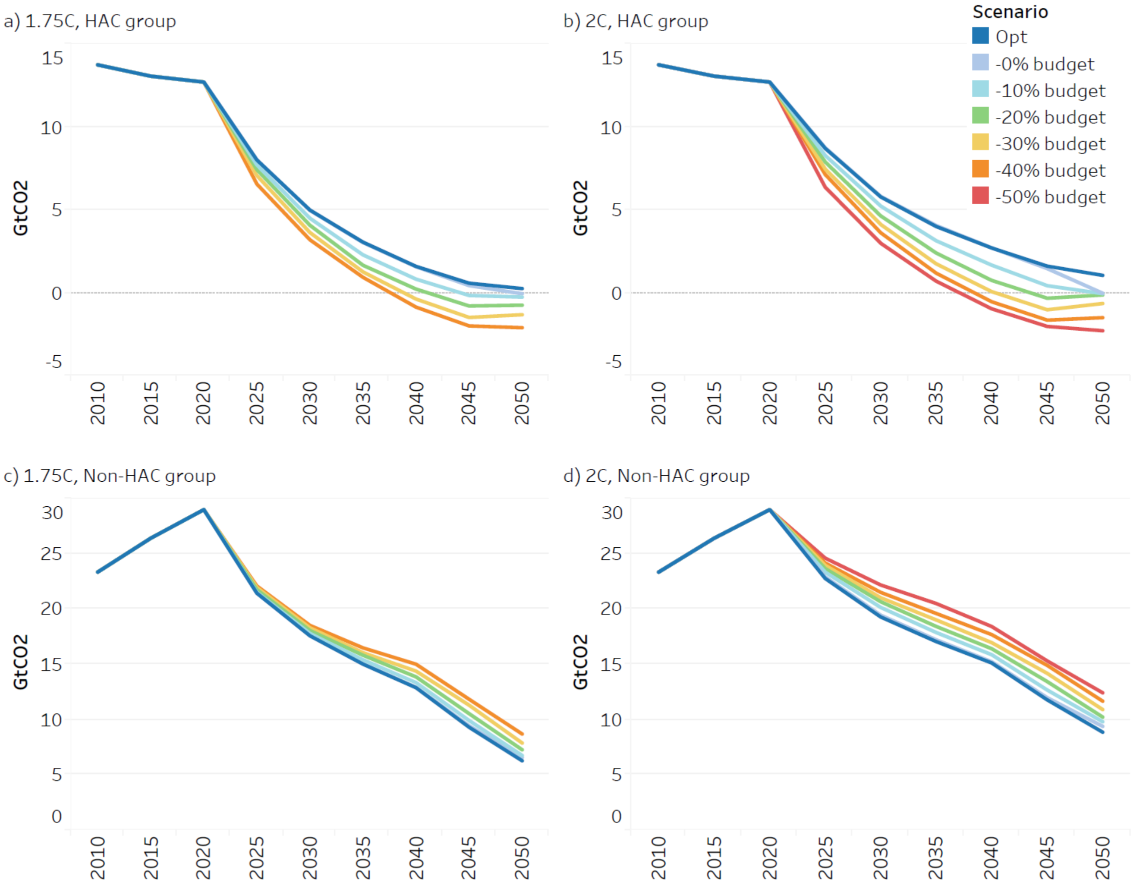

**Figure 8. Global $CO_2$ emission trajectories for 'leadership- driven' scenarios, 2010-2050.** HAC group $CO_2$ emissions under a) 1.75°C and b) 2°C. Non-HAC emissions under c) 1.75°C and d) 2°C. The 'Opt' scenario refers to the global least-cost case, while all other scenarios meet net-zero $CO_2$ emissions in 2050, and have adjusted budgets at the levels indicated. Note that the 1.75°C -50% budget case did not solve, and is therefore omitted from the plots.

The equivalent trajectories for all GHGs are shown below in Figure 9, showing a similar pattern as shown for $CO_2$ emissions. For the HAC group, the strongest action (under 1.75C(-40) and 2C(-50) budget levels) pushes the group towards net zero GHG emissions by as early as 2045. This does not mean all HAC countries reach net-zero GHGs by this date, with some variation in reductions across the grouping. At the same time, the non-HAC group sees a less demanding GHG reduction pathway as a function of budget level.

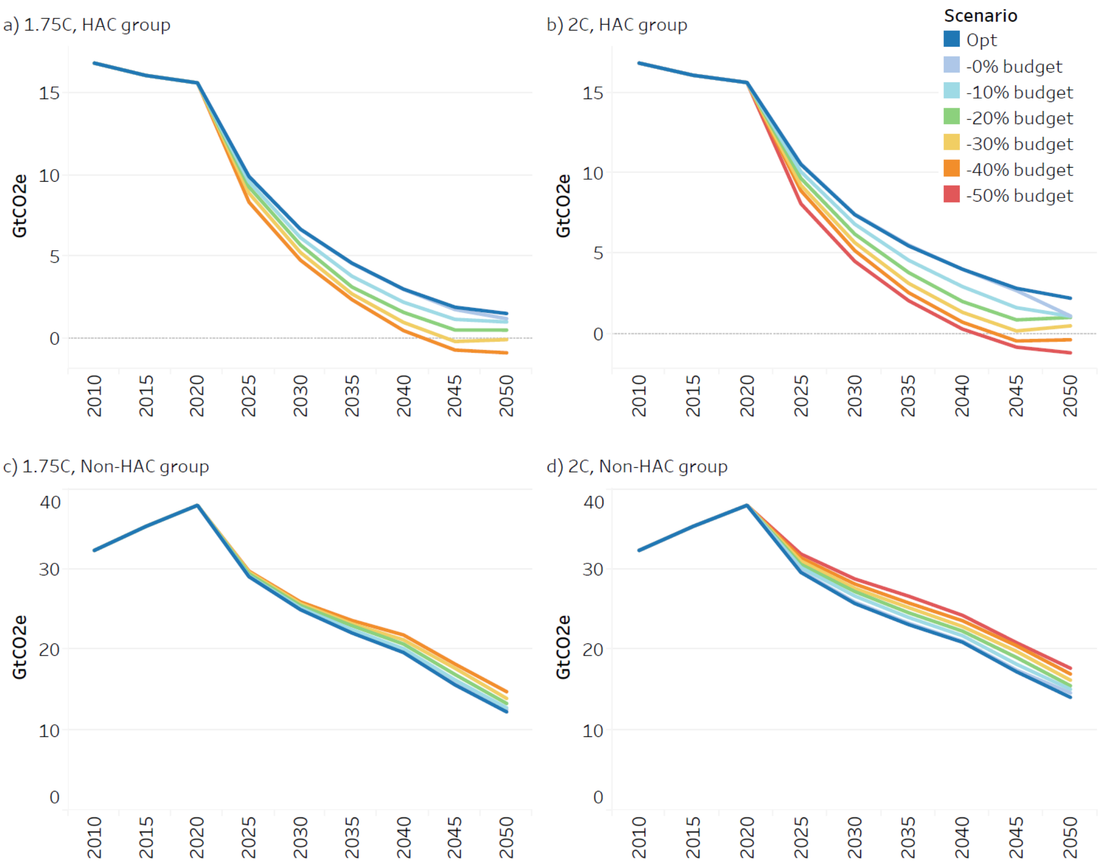

**Figure 9. Global GHG emission trajectories for 'leadership- driven' scenarios, 2010-2050.** HAC group GHG emissions under a) 1.75°C and b) 2°C. Non-HAC GHG emissions under c) 1.75°C and d) 2°C. The 'Opt' scenario refers to the global least-cost case, while all other scenarios meet net-zero $CO_2$ emissions in 2050, and have adjusted $CO_2$ budgets at the levels indicated. Note that the 1.75°C -50% budget case did not solve, and is therefore omitted from the plots.

A selection of important metrics of the underlying energy system transition is shown in Figure 10 for the 1.75C(66) HAC cases. For the non-HAC group under this scenario, compared to the 1.75C(66) case:

- The level of $CO_2$ captured by CCS in 2050 is 9% and 40% lower under the -10% and -40% cases. In cumulative terms to 2050, the reductions are 9% and 42% lower. The corresponding values for BECCS are 19% and 88% lower in 2050, and in cumulative terms 18% and 85% lower.
- While post-2030, gas production declines in all cases, this decline is slowed due to additional headroom for more cumulative emissions in these regions. Cumulative gas production (to 2050) is therefore 1.9% and 8% higher under the -10% and -40% cases. For oil production, the increase in levels is lower at 0.6% and 3.4%.
- The need for hydrogen fuels at the levels observed in the global least-cost case is reduced, with reductions in cumulative production of 2.5% and 6.2% under the -10% and -40% cases.
- Oil use in the transport sectors, whilst declining, does so at a slightly slower rate, with cumulative consumption reducing by 1.6% and 6.2% in the -10% and -40% cases.

However, certain metrics for the non-HAC grouping show little or no sensitivity to the scale of $CO_2$ budget reallocation. Wind and solar deployment remains consistently rapid across the explored sensitivities, indicating the prominent role for variable renewables in future power systems across the globe, as was described for the global least cost scenarios in section 3. The share of electricity in road transport which rises on essentially the same trajectory to 45% by 2050 for all budget scalings. Finally, total annual electricity demand grows at a similar pace in all cases, demonstrating a consistent picture of increasing electricity demand in future. Overall, the non-HAC group does have more time to reduce emissions, with a slower mitigation rate. Importantly, the marginal cost of abatement reduces (as measured by the shadow price in the model) by around 9.5% under the -40% case, from \$900 down to \$815/$tCO_2$ in 2050. The shadow price in 2050 increases to over \$1300 /$tCO_2$ in the HAC group, or 44% higher.

More action is required in the HAC group, as reflected by the increasing mitigation rate. This includes an increase in the deployment of lower carbon technologies such as CCS or hydrogen, and, crucially, the more rapid phase out of domestic fossil fuel production and the use of these fuels in sectors, such as oil in the transport. For example, under the most stringent case, cumulative CCS is 87% higher than in the global least-cost 1.75C(66) by 2050 (117% higher for BECCS), while hydrogen production (largely via electrolysis and biomass gasification) is about double in the cumulative terms.

It is important to note that bioenergy consumption does increase significantly, largely enabled by trade, with domestic production in the HAC grouping already at its limits before rebalancing the budget. This transfer of biomass from non-HAC to HAC regions facilitates the ability to increase BECCS deployment. This redistribution of biomass can help ensure that the world's supply of sustainable low-carbon biomass is used most effectively for the global climate effort (i.e. with CCS). It may be that very large-scale increases in the import of biomass for BECCS could be a candidate for effort-sharing of mitigation credits between importer and exporter countries under the mechanisms of Article 6 of the Paris Agreement.

These increased rates of deployment could have strong economic and technological benefits for non-HAC regions while at the same time providing first mover advantages for HAC regions. Fossil production decline also has to be faster, highlighting how HAC regions can lead the way; in the -40% case, gas production (cumulative) reduces by 23% relative to 1.75C(66), while for oil the reduction is 20%. A similar reduction is observed for oil use in transport across the HAC group.

It is also insightful to observe what does not change across these rebalanced cases for the HAC. In a similar vein to the non-HAC regions, this includes metrics for electricity production and use, again suggesting that low carbon power generation is something that all regions should be pushing forward with, irrespective of the specific climate target (as highlighted in section 3).

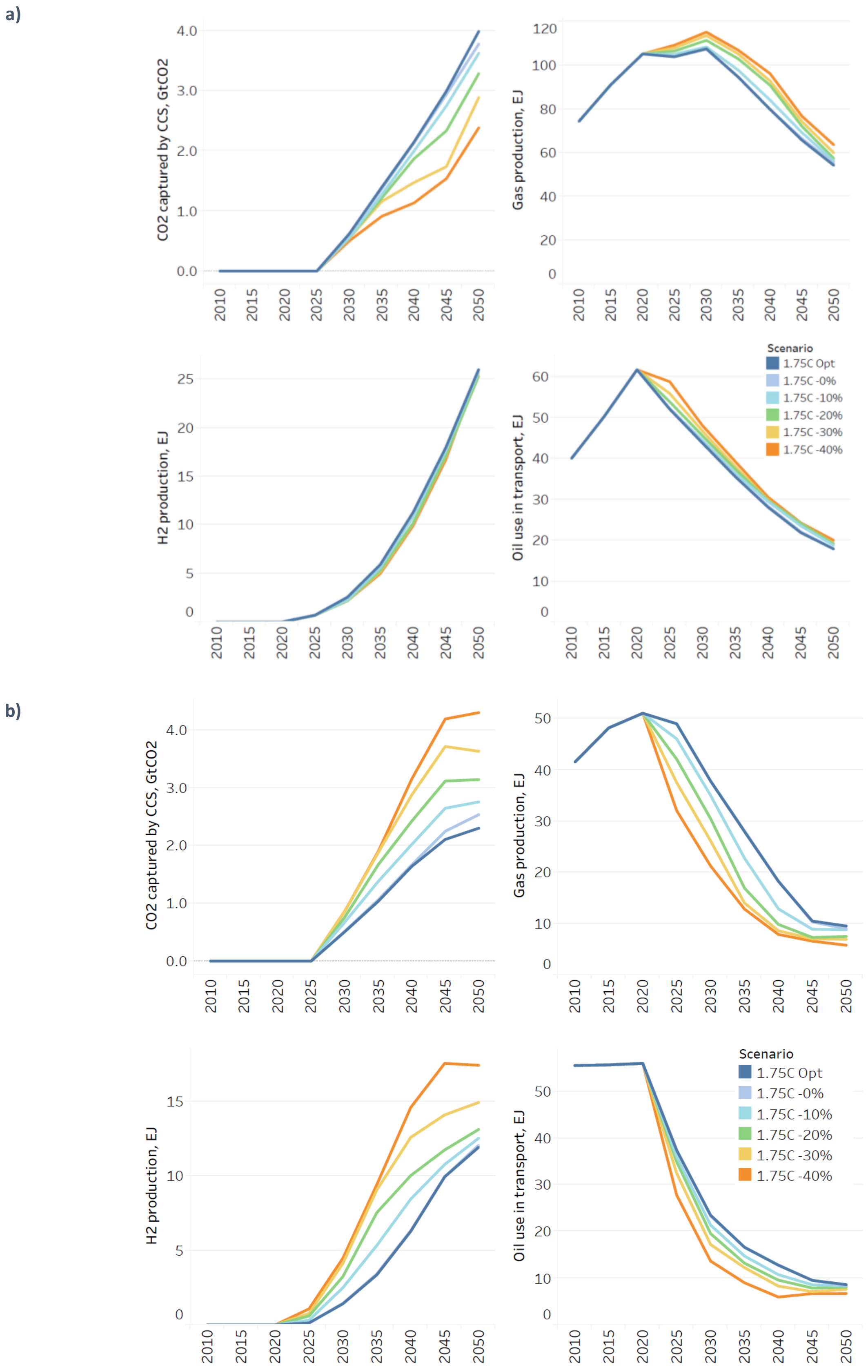

**Figure 10. Non-HAC (a) and HAC (b) group metrics under the 1.75°C leadership-driven scenarios.** All metrics are for the period 2010-50, and for both a) and b) include top-left) $CO_2$ captured by CCS; top-right) Gas production; bottom-left) H2 production; and bottom-right) oil use in transport. The 'Opt' scenario refers to the global least-cost case, while all other scenarios meet net-zero $CO_2$ emissions in 2050, and have adjusted budgets at the levels indicated.

The 2°C case can be found in Appendix 3, and reinforces the observations described here. However, the headroom for the non-HAC group is somewhat higher due to the larger budget allocation under this less stringent case.

## The UK as a leader

Drawing out the picture for the UK in the context of the leadership-driven scenarios, in Figure 11 and Figure 12 we see a similar set of both $CO_2$ and GHG emission reduction pathways to the wider HAC grouping. In this figure, we once more plot the global least-cost scenario as “Opt” for each case and then the HAC scenarios coloured by their budget scaling. For 1.75C(66) we see a greater requirement for negative $CO_2$ emissions as the HAC emissions budget is reduced. In line with this, the year the UK achieves net-zero $CO_2$ emissions is brought forward from 2050 to between 2030-35 in the most stringent runs while net-zero GHG emissions is reached in 2045 for -10% budget and occurs just after 2035 in the most ambitious scenarios. This earlier date is only enabled by a strong reduction in energy service demands (driven by increasing price effects) and large increases in imported biomass, allowing for the higher deployment of BECCS. Further work is needed to assess whether such rapid action in the near term could feasibly be delivered, in particular with less reliance on imported biomass and deeper reductions in the sources of residual emissions.

The pathways look similar for 2C(66) albeit with less negative emissions and slightly later net-zero years. However, across both cases, net-zero GHG emissions occurs no later than 2050 for all budget stringencies tighter than the base 0% option.

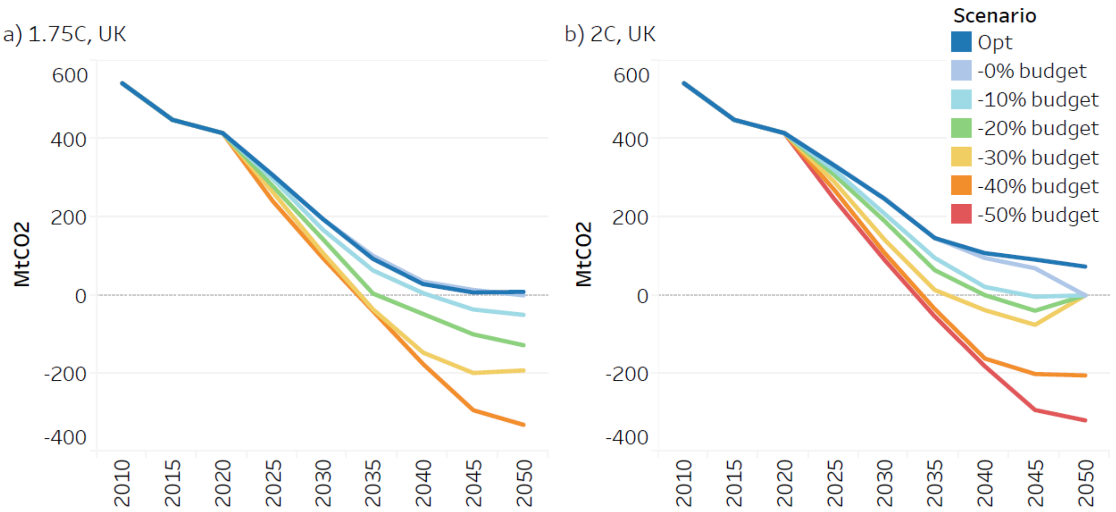

**Figure 11. UK $CO_2$ emission trajectories for ‘leadership-driven’ scenarios, 2010-2050.** $CO_2$ emissions under a) 1.75°C and b) 2°C. The Opt scenario refers to the global least-cost case, while all other scenarios meet net-zero $CO_2$ emissions in 2050, and have adjusted budgets at the levels indicated. Note that the 1.75°C 50% case did not solve, and is therefore omitted from the plots. For selected 2C cases, having gone negative, emissions can increase back up to zero before 2050 and still allow for a balanced budget. This is a feature of the constraint implementation in the modelling.

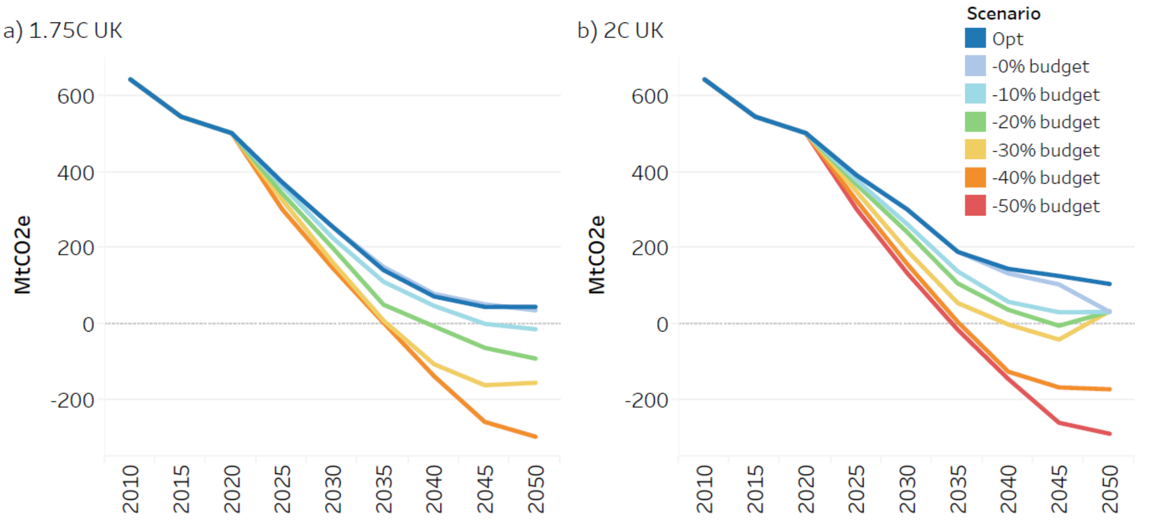

**Figure 12. UK GHG emission trajectories for 'leadership- driven' scenarios, 2010-2050.** GHG emissions under a) 1.75°C and b) 1.75°C. The Opt scenario refers to the global least-cost case, while all other scenarios meet net-zero $CO_2$ emissions in 2050, and have adjusted budgets at the levels indicated. Note that the 1.75°C 50% case did not solve, and is therefore omitted from the plots. For selected 2C cases, having gone negative, emissions can increase back up to zero before 2050 and still allow for a balanced budget. This is a feature of the constraint implementation in the modelling.

Figure 13 presents a number of key metrics for the UK transition. It shows that the amount of $CO_2$ captured in the UK increases for both temperature targets as the HAC carbon budget is reduced with the vast majority of the increased utilisation of CCS going toward BECCS to generate negative $CO_2$ emissions. For instance, hydrogen production from biomass gasification with CCS rapidly scales up as budget stringency increases. Taking a more sectoral perspective, we see that tighter global HAC budgets lead to a more rapid reduction of oil use in transport down to its aviation driven floor. This trend is then reflected in the uptake of hydrogen and electricity in this sector, where the former mainly fuels heavy goods vehicles and shipping while the latter dominates in the car sector. $H_2$ use shows some sensitivity to HAC budget as it ramps up earlier for tighter budgets while electricity on the other hand is consistently deployed rapidly across the rebalanced scenarios. For example, in the car sector oil use is essentially phased out (i.e. has dropped to very low levels) by 2040 for the 1.75C(66) Opt case with this phase out brought forward to 2030 for the most stringent HAC budget.

While Figure 13 displays metrics that do change with the HAC budget, it is also important to discuss those that are consistent, or largely so, across the sensitivities as these may be considered least-regret options in the UK's decarbonised energy system based on our analysis. These include a substantial growth in electrification irrespective of budget, the rapid phase out of unabated fossil electricity generation by 2030 and the build out of wind generation capacity.

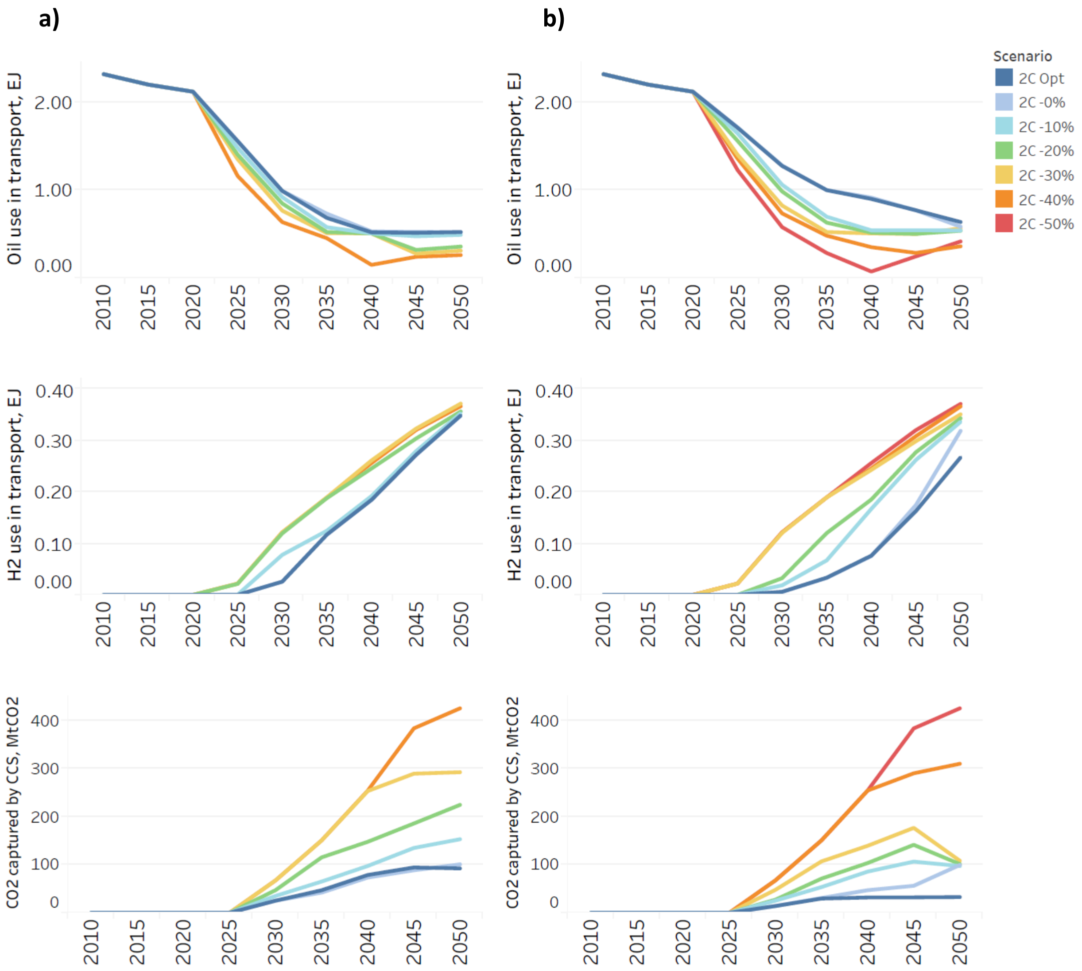

**Figure 13. UK metrics for leadership-driven scenarios under a) 1.75°C and b) 2°C targets** Metrics include oil use in transport (top); $H_2$ use in transport (middle), and $CO_2$ captured by CCS (bottom). The 'Opt' scenario refers to the global least-cost case, while all other scenarios meet net-zero $CO_2$ emissions in 2050, and have adjusted budgets at the levels indicated.

# 5. Afforestation and lower demand sensitivities

**Key results**

- Afforestation has the potential to play a larger sequestration role than BECCS if abandoned agricultural land is used for forest rather than energy crops. As it is associated with much lower supply chain risks and multiple co-benefits such as ecosystem services and tourism, it should therefore be given stronger consideration as an option.
- In the 2°C case, large-scale afforestation instead of energy crop production significantly reduces BECCS dependency. In the 1.5°C case, it significantly reduces the carbon budget exceedance observed in the global least-cost case.
- The demand sensitivity tests recognise i) the uncertainty inherent in SSP2's "middle of the road" demand projection, and ii) that opportunities exist within these projections for demand reductions. Using lower energy service demands (SSP1) in the 1.5°C case reduces final energy consumption and almost halves the level of carbon budget exceedance observed in the global least-cost case.
- Combining the lower demands and large-scale afforestation removes the budget exceedance in the 1.5°C case. In the 2°C case, the reliance on BECCS is almost entirely removed.
- Lowering service demands in line with SSP1 has a larger effect on the energy mix than afforestation, as it reduces the required energy demands across sectors. However, the addition of afforestation has a bigger effect on the marginal cost of mitigation as it substantially decreases the level and rate of transformation required by the energy system, especially in the 2°C case.

Two scenarios have been run to explore critical uncertainties in the modelled trajectories for the global effort to achieve the Paris Agrement, firstly the potential role of large-scale afforestation as an alternative to BECCS to sequester $CO_2$, and secondly, lower energy service demand projections. Both are crucial for exploring the feasibility of more ambitious mitigation targets, and the supply-side dependency on BECCS technologies. Both scenarios are run for 1.5°C and 2°C targets (66% probability), and combined to assess the impact of lower demand and higher afforestation. A detailed description of the scenario set-up is provided in Appendix 2.

The afforestation scenarios, labelled '2C (66) Aff' and '1.5C (66) Aff' are run with the $CO_2$ trajectory shown in Figure 14 (green line) representing $CO_2$ emissions from land-use. This assumes sequestration by long-term forest planted on abandoned agricultural land instead of energy crops, which is thought to be the most effective forestry method for carbon sequestration[18]. The area of land assumed available for afforestation or energy crops is 207 Mha by 2050 (derived from the IMAGE and Ricardo models [19,20]), which is equivalent to 24% of the land area of Brazil. 40% of this area is considered to be in Africa, 26% in Central and South America, and 17% in Asia. Europe, including the UK, would contribute less than 5% (10 Mha). Note that in the scenarios reviewed for SR1.5, approximately 300 Mha is converted to forest by 2050 in the S2 scenario, along with a similar area for energy crops. In the LED scenario, approximately 300 Mha is converted to forest but energy crops are not employed up to 2050[21].

The fixed $CO_2$ sequestration trajectory shown below is used to test the role large-scale afforestation could play in offsetting emissions in the energy system and reducing the reliance on BECCS. High resolution spatial modelling is required to establish the soil and climatic suitability of land parcels for forestry with different species mixes. It is important to note that time-lags and costs associated with establishing new forest as a carbon sink are not considered in this modelling.

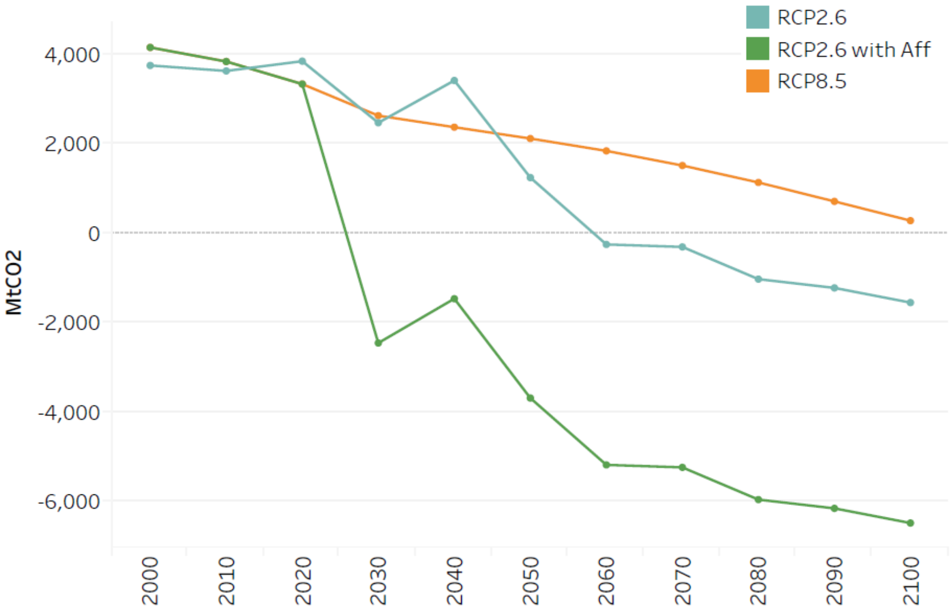

**Figure 14. Land-use $CO_2$ emissions (fixed to RCP 8.5 reference up to 2020)**

## Afforestation scenarios

The estimated afforestation modelled in these scenarios provides a higher level of negative emissions in 2050 than those from BECCS in the core scenarios, at approximately 5 $GtCO_2$/yr compared to an estimated 4 $GtCO_2$/yr via BECCS. Afforested land is also considered to provide a small amount of residues for use in BECCS. However, it is not quite sufficient to allow the 1.5°C (66%) case to find a pathway that does not exceed the carbon budget. In the 2C (66%) case, the higher afforestation sequestration potential reduces the rate of mitigation across the energy system. This allows the model to choose slightly less expensive options, and reduces commodity and electricity prices compared to the global least-cost scenarios. Due to the model's elastic demand feature, this results in slightly higher final energy demand in the afforestation case.

Consistent with this, the marginal cost of mitigation is lower when afforestation is deployed, particularly as it is introduced into the model as a low to zero cost option. In the 2°C case with afforestation, the marginal cost peaks in 2050 at 231 $/$tCO_2$ with afforestation, as opposed to 435 $/$tCO_2$ in the global least-cost scenario. Note, the marginal cost cannot be considered in the 1.5C (66) Aff case as the backstop is deployed.

Under both climate targets, large-scale afforestation reduces the reliance on BECCS to mitigate carbon emissions (Figure 18). In the 2°C case, cumulative $CO_2$ captured by BECCS is more than halved, from 200 to 83 Gt. In the 1.5°C case, BECCS is reduced less, from 271 to 169 Gt, due to the higher stringency of the target. With the 1.5°C target, all the potential biomass is used, while under the 2°C target, approximately the same proportion of the available woody biomass is used in the core and afforestation scenarios (under which the available biomass is lower) (Figure 15).

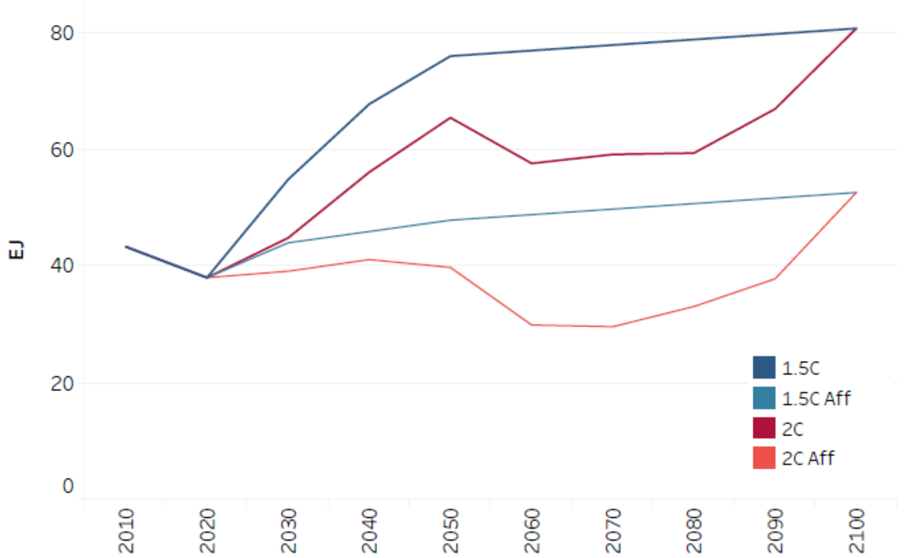

**Figure 15. Global primary biomass production of energy crops and woody biomass (EJ) under afforestation (Aff) scenarios.** The 1.5°C scenarios after 2030 are at the maximum level of production.

The large negative emissions from afforestation allow the model a little more flexibility in the rate of energy system decarbonisation under the 2°C target. In the 2°C case with afforestation, the rate at which fossil fuels are phased out of the power system is slightly reduced, most notably for gas, though we note that changes are marginal, given the simple representation of afforestation in this modelling exercise and the large uncertainties over the timing and rate of carbon dioxide removal that could be achieved.

## Lower demand scenarios

Lowering the service demands to be in line with an SSP1 scenario reduces the final energy consumption by approximately 11% in 2050 and by 30% in 2100 (Figure 16), requiring a smaller energy system compared to that in the global least-cost scenarios (based on SSP2 demand assumptions).[10] Under the 1.5°C ambition, this is not sufficient to avoid budget exceedances to the level of 144 $GtCO_2$, or a third of the remaining carbon budget, over the model time horizon, although this is about half of the exceedance observed under the equivalent global least-cost scenario. Despite the substantial reduction in demands, it is still challenging to mitigate in the pre-2050 period when stronger mitigation is needed.

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[10] Key drivers of energy service demands differ between the SSP1 and SSP2 scenarios. In SSP1, the global population rises to 6.9 bn people in 2100, compared to 9.0 bn in SSP2; in SSP1, global GDP rises to $566 tn by 2100, compared with $539 tn in SSP2.

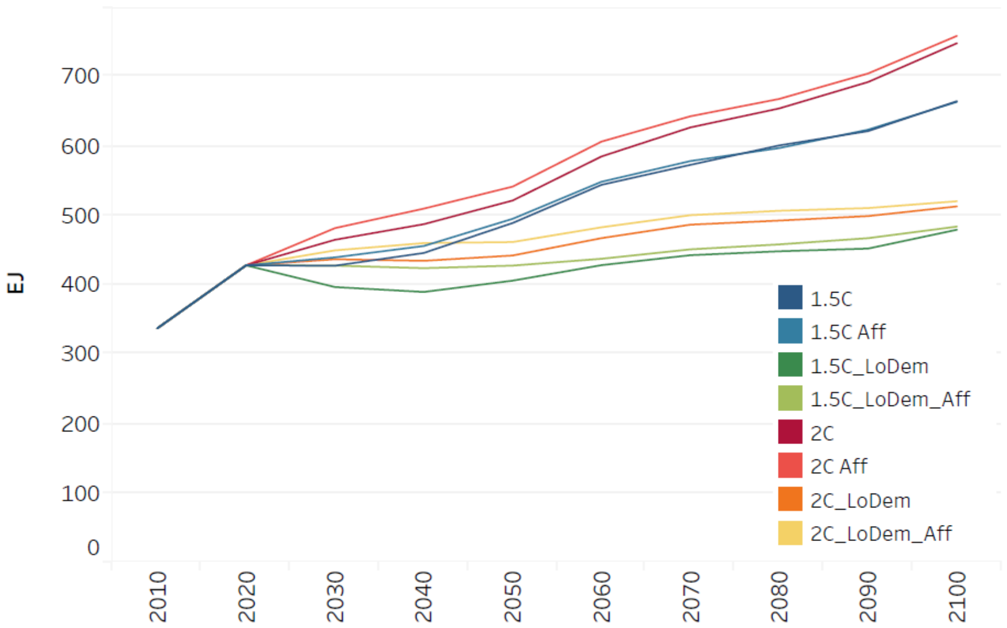

**Figure 16. Total final energy consumption (EJ) under afforestation (Aff) and lower demand (LoDem) scenarios, 2018-2100**

The effect of lower demands on the use of BECCS differs between the two climate target scenarios. Under the 2°C target, the requirement for BECCS is reduced from 200 Gt to 147 Gt, while total bioenergy production falls from 114EJ/yr to 94EJ/yr in 2100. However, under the 1.5°C target, bioenergy is not reduced but hits the maximum level of 115EJ in 2100, as per the global least-cost scenario. Under the more stringent climate target, lowering demand shifts the use of biomass resources between sectors; in the 1.5°C case with lower demands, it is cost-optimal to divert biomass away from transport fuels and direct use in industry and instead use it for BECCS power generation. Due to the higher $CO_2$ capture efficiency for BECCS power (90% as opposed to 50%), this increases the $CO_2$ captured by BECCS from 271 Gt to 302 Gt over the century.

For the rest of the global energy mix, reducing service demands has the effect of reducing the use of fossil fuels. In the 2°C case, oil, gas and coal production are all reduced by lower demand. The strongest effect is on gas. In the 1.5°C case, coal is already reduced to very low levels in the central demand case (below 26EJ/yr by 2045) but lowering demands reduces oil and gas production substantially from 2020 onwards.

Due to these changes, the marginal cost of mitigation is lower for both climate targets (Figure 17). In the 2°C case, the marginal cost of mitigation is reduced by approximately one third (compared to the core case). Note, the marginal cost is reduced more by the addition of afforestation than it is by lowering the demands alone. For the 1.5°C case, the marginal cost cannot be considered due to the use of backstop.

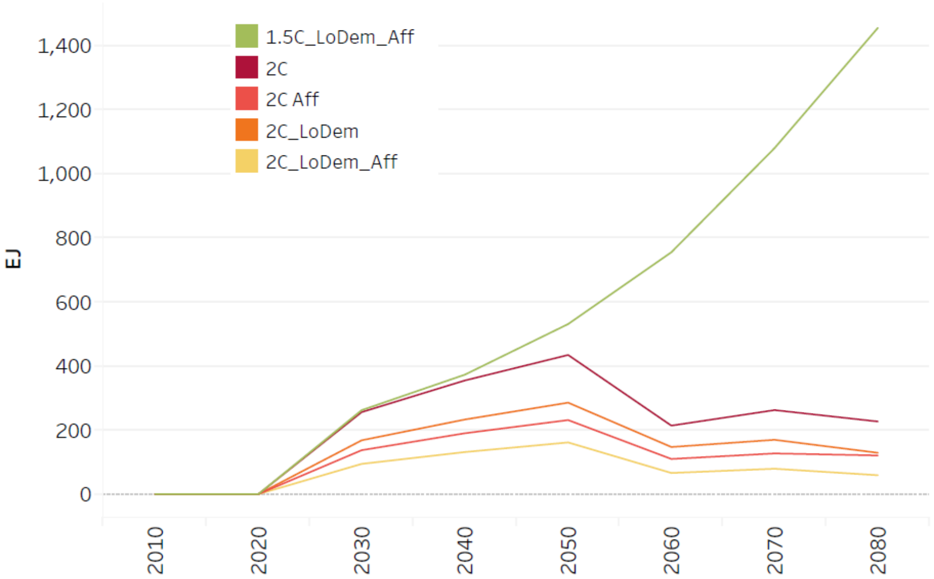

**Figure 17. Marginal cost of $CO_2$ mitigation under afforestation (Aff) and lower demand (LoDem) scenarios.** 1.5°C scenarios that include backstop have been omitted.

## Combined scenarios of afforestation and lower demand

Under the 1.5°C target, a combined low demand-high afforestation scenario removes the need for the backstop. The marginal cost of mitigation is comparable to the 2°C scenarios up to 2040 (373$/t$CO_2$ in 2040), and much lower than any other 1.5°C scenario. After 2040, it rises steeply, indicating much of the energy emissions mitigation is undertaken in the second half of the century (Figure 17).

The combined effect of afforestation and demand reduction on the reliance on BECCS for $CO_2$ capture differs between the 2°C and 1.5°C cases. Under 2°C, reducing the demands or adding afforestation all reduce the $CO_2$ capture by BECCS. Applying both decreases the level of capture by BECCS by 82%. Under 1.5°C, it is so challenging to decarbonise the energy system sufficiently that all biomass is used even in the low demand scenario and applying both afforestation and lower demand reduces the $CO_2$ capture by BECCS by only 31%.

In the 2°C case, biomass production is strongly reduced compared to the other 2°C scenarios; rather than doubling over the century as in the energy crops case, it remains close to current levels and is reduced to below 40EJ/yr in the second half of the century. Under 1.5°C case, biomass production is steady at 80EJ to the end of the century, as under the stringent 1.5°C target, almost all the available biomass is used, even with the low demands and afforestation.

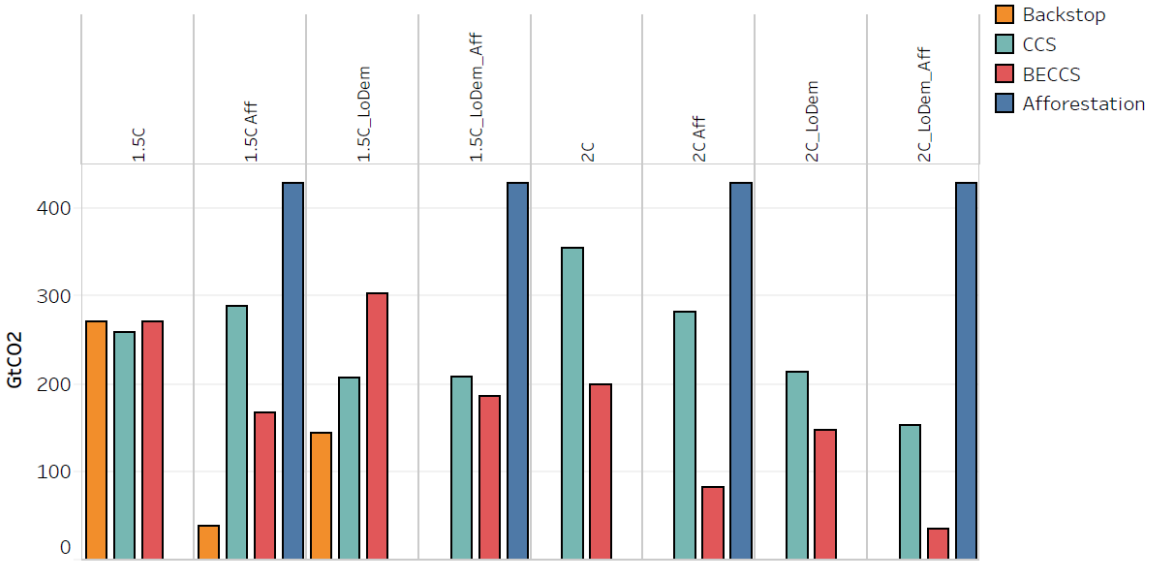

Figure 18. Cumulative $CO_2$ emissions captured by CCS (w/ and w/out BECCS) under afforestation (Aff) and lower demand (LoDem) scenarios, 2018-2100

# 6. Insights and conclusions

This reports reinforces those of other analyses, that all regions need to contribute to the global efforts to reduce emissions of greenhouse gases, if the types of climate objectives set out in the Paris Agreement are to be met. This means global $CO_2$ emissions being net-zero or near-zero by or soon after 2050 if warming is to be kept well-below the 2°C limit, as illustrated by the modelled 1.75°C case.

However, given equity and capability considerations under the Paris Agreement, developed countries such as the UK need to show leadership in undertaking earlier and stronger emission reductions. The analysis shows that this means more rapid draw down in the production and use of fossils fuels, the development and use of alternative low carbon fuels, and to some extent, the use of negative emissions for hard-to-mitigate sectors. Based on the option to increase the uptake of BECCS, we highlight that this could be enabled to some extent by the transfer of bioenergy via imports, but more detailed work is needed to explore to what extent this could be replaced with additional reductions in the sources of residual emissions across the economy.

Increased action by the UK and other partner countries could provide emissions 'headroom' for low carbon transitions in other parts of the world. The analysis shows that this can lead to changes that could help developing countries through the transition to low carbon energy systems, including a lowering of mitigation costs, providing more time to switch away from fossil fuels, and reduced dependency on CCS/BECCS deployment. Crucially, we find that this headroom does not slow the required large-scale deployment of renewable generation technologies, which continue to expand at pace due to their lower cost relative to fossil-based generation.

It is important to note that while there is the opportunity for stronger ambition for countries such as the UK, the coalition of countries taking stronger action, as simulated in this modelling, only account for 23% of the global $CO_2$ budget share to 2050, meaning that ultimately climate goals can only be met with strengthened action across all regions. This is especially true for the more ambitious end of the Paris Agreement long-term temperature goal.

Strengthening of the climate policy both in the UK and in other developed countries in this analysis has highlighted an increased dependency on negative emissions from BECCS. For example, the 1.75°C case, with a carbon budget of 800 $GtCO_2$ deploys BECCS capture at a level of 260 $GtCO_2$ (plus non-bioenergy based CCS at a similar level). Whilst these scenarios do not show the dependency of other scenarios, for example those used in the SR1.5, the scale of deployment is still high, and risks lock-in to continued fossil fuel use if such technologies are not sufficiently scaled (as BECCS reduces the required reductions in fossil fuel use due to offsetting it provides).

Other options need to be explored that are not adequately represented in the modelling, including those focused on the industrial and transport sectors, where residual emissions were observed to be highest. This includes both options that can help decarbonise the supply of energy being used in these sectors, additional efficiency gains to reduce the amount of energy required, and demand-side measures that reduce the amount of energy service demand, the impacts of which were illustrated in the modelling of the lower demand scenario. These may allow the strengthening of UK ambition as simulated in these scenarios with a reduced reliance on achieving this with large increases in the amount of imported biomass.

A further option to reduce dependency on BECCS, in addition to lowering demand for energy services, is through large-scale afforestation. As shown, this has the potential to play a larger sequestration role than BECCS if abandoned agricultural land is used for forest rather energy crops.

Individually, neither large-scale afforestation nor substantial reduction of service demands is sufficient to remain within the 1.5°C carbon budget. However, the combination of these measures at significant scale shows how a 1.5°C level of ambition could be met.  The combination could also removes the reliance on BECCS almost entirely in the modelled 2°C case.

Both lowering service demands and large-scale afforestation present significant challenges and opportunities. Afforestation is a readily available CDR technology, while BECCS is a less mature option with substantial supply-chain risks. However, careful consideration of biodiversity and the land-use, land-use change emissions balance is still required along with planning and regulation of the forest management methods to ensure the long-term regeneration of natural forests rather than commercial plantations. Lowering service demands through energy efficiency and energy demand reductions measures offers potential co-benefits for energy security and access but challenges for effective behavioural interventions.

In the absence of these measures at scale, the analysis also usefully shows why a 1.5°C target is not met in this modelling framework, through comparison with other scenarios. This is due to a lower global biomass potential, lower CCS deployment rates, and high residual emissions in industry and transport. Efforts should focus on an improved understanding of how these residual emissions can be reduced, as opposed to exploring higher bioenergy potentials (given sustainability concerns) or stronger deployment of CCS (due to the already strong reliance in the modelling on this yet-to-be-scaled solution).

To conclude, if the UK, as part of a group of developed country partners, made efforts to strengthen their climate policies beyond the global least-cost contribution, our modelling indicates that this would provide some headroom for other regions, develop technological solutions more rapidly, including cost reductions through research and innovation, and inform how effective policy packages can be developed. This increase in near term ambition could also help focus the necessary attention on how to tackle those hard-to-mitigate sectors and solutions that have perhaps not been given sufficient attention to date, including afforestation and demand-side measures.

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# Appendix 1: TIAM-UCL scenario assumptions

The primary assumptions used in TIAM-UCL can be found in Table 5 below.

**Table 5. Core assumptions used in the TIAM-UCL scenarios**

| Category | Description | Values | | | | Units | Source |
|---|---|---|---|---|---|---|---|
| | | 2030 | 2050 | 2080 | 2100 | | |
| **1. Demand drivers** | Population and growth drivers, based on the SSP2 'Middle of the Road' scenario narrative. Region specific values used but global values presented below. | | | | | | [22] |
| | Population | 8.3 | 9.2 | 9.4 | 9.0 | billion | |
| | GDP | 17 | 25 | 42 | 59 | 000 US$2005/cap | |
| | Households | | | | | | |
| | Energy service demands are based on the above core drivers. Some adjustments have been made to energy service demands to ensure final energy demand globally falls within the SSP2 marker model (MESSAGE) range. As SSPs are independent of climate ambition, defining the socio-economic backdrop that a given climate ambition has to be achieved within, the demands for SSP2 in TIAM have been tuned to match the marker model's base/reference SSP2 run with no climate constraints. | | | | | | |
| | | | | | | | |
| **2. Resource assumptions** | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Bioenergy | First generation fuels are represented as bioliquids (bioethanol and biodiesel from crops which might compete with food crops for land) and biomethane (gas captured from controlled landfill sites). Four types of second-generation bioenergy feedstock distinguished: **i)** Solid biomass (BIOSLD), comprising woody residues from forestry and agriculture (stems and branches, unmerchantable trees from pruning and thinning operations, residues from sawmill and plywood production, timber and paper scrap, aboveground stalks, husks, shells and cobs); **ii)** Energy crops (BIOCRP), comprising second generation purposely grown energy crops (grassy and woody bioenergy crops); **iii)** Municipal waste (BIOBMU), comprises wastes produced by households, industry, hospitals and the tertiary sector that are collected by local authorities; and **iv)** Industrial waste (BIOBIN), Solid and liquid products (e.g. tyres, sulphite lyes (black liquor), animal materials/wastes), usually combusted directly in specialised plants to produce heat and/or power. For each of these fractions cost supply curves are specified within the model for each of the 16 regions, i.e. amount of biomass available at different costs in each region. | | | | | | |
| | Cost range for solid biomass: 4-16 $/GJ, energy crops: 9-15 $/GJ, no cost for waste fractions. To avoid competition for land, energy crops are assumed to be grown only on marginal and degraded land. Note that only solid biomass and energy crops fractions can be used for BECCS. | | | | | | |
| | Solid biomass (central) | 43 | 45 | 48 | 50 | EJ/y potential | [23] |
| | Energy crops (central) | 17 | 31 | 31 | 31 | EJ/y potential | Marginal land availability and energy crop yields from Ricardo-AEA. (2017). Biomass Feedstock Availability. Final report for BEIS. Supply cost curves based on [24] |
| | MSW (central) | 17 | 27 | 27 | 28 | EJ/y potential | TIAM-ETSAP |
| | | | | | | | |
| Oil | For oil, resources include current conventional 2P reserves in fields that are in production or are scheduled to be developed, reserve growth, undiscovered oil, Arctic oil, light tight oil, natural gas liquids, natural bitumen, extra-heavy oil, and kerogen oil. The latter three of these are the unconventionals. | | | | | | Oil resource supply curves based on [25] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Gas | For production, there are eight categories of ‘conventional’ and ‘unconventional’ gas modelled: current conventional proved and probable (2P) reserves that are in fields in production or are scheduled to be developed, reserve growth, undiscovered gas, Arctic gas, associated gas, tight gas, coal-bed methane, and shale gas. Individual supply cost curves for each of the eight categories are estimated for each region. | | | | | | Gas resource updates based on [26] plus more recent updates from Dan Welsby's PhD. |
| Coal | Coal resources in TIAM are distinguished between hard coal, which includes anthracite, bituminous and sub-bituminous coal, and lignite (soft brown coal). | | | | | | |
| | | | | | | | |
| **3. Power generation** | | | | | | | |
| Solar | Solar costs around $1500/kW (average) in 2017, fallling to $530/kW in 2050. ~6500 GW in 2050 in terms of deployment in 2C case | 890 | 530 | | | $/kW (2017) | IRENA / BNEF [see *Scen_SolarTechRuns*] |
| | Using these cost trajectories, give us a rate of deployment that is consistent with around a 23% learning rate. | | | | | | |
| | Maximum build rate of new capacity each year is set at 30% of existing capacity in line with recent solar PV build rates[11] | | | | | | |
| Wind (on) | Average 2017 costs in the region of 1400 $/kW | 1100 | 600 | | | $/kW (2017) | IRENA / BNEF |
| Wind (off) | Average 2017 costs in the region of 4000 $/kW | 3000 | 1500 | | | $/kW (2017) | IRENA / BNEF |
| | Total wind capacity additions (i.e. on and offshore combined) per year is set at 30% of existing capacity. | | | | | | |
| | | | | | | | |
| **4. CCS** | The current set-up of the model reflects revisions undertaken as part of the recent GCCSI report. CCS applications are available in the following sectors – electricity and heat production, hydrogen production, biofuel production (via Fischer Tropsch processes) and industry for combustion emissions from process heat production in iron and steel, non-metallic minerals and other industry sub-sectors. There is also a CCS technology that captures CO2 process emissions from the use of petrochemical feedstocks. Biomass in TIAM-UCL, which can be used in combination with CCS to generate so-called ‘negative emissions’ (BECCS), is assumed to be carbon neutral, and while land-use is considered here, there is no competition with other uses such as food production – such an analysis would require a general equilibrium setting. | | | | | | Ekins, Hughes et al. (2017). The role of CCS in meeting climate policy targets. http://hub.globalccsinstitute.com/sites/default/files/publications/201833/report-role-ccs-meeting-climate.pdf |

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[11] http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/2018_iea-pvps_report_2018.pdf

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cost and performance information can be found in the GCCSI report, and notably reflects updates in Rubin et al. 2015. Captures rates of 50-90% are assumed, depending on technology, with power generation at the upper end of this range and FT biofuel production at the lower end. | | | | | | [27] |
| | CCS can grow at between 2-5% for annum (industry, power at the upper end), starting from 2030. Based on the IPCC AR5, looking at median to upper quartile range of 15-24 GtCO2 by 2100. | | 7 | 13.6 | 15 | GtCO2 capture (median IPCC) | |
| | | | | | | | |
| **5. End use sectors** | | | | | | | |
| BEVs | By 2050, EVs around 46% of their current day cost, and at price parity with conventionals in 2030. | | | | | | BNEF |
| | | | | | | | |
| **6. Climate constraints** | The climate module is calibrated to MAGICC17, with values from the probability distribution selected to give a 60% chance that the temperature rise will remain below any level reported. | | | | | | [6] |
| | The model can be run to allow temperature overshoot prior to 2100. Net negative accounting is also switched on, meaning that the system CO2 level can go negative, through the implementation of NETs. | | | | | | |
| | For the CCC scenarios, the model is run with carbon budgets (as shown in the sheet 'Content'), with the non-CO2 trajectory constrained in line RCP2.6 assessments. The climate module is used to control for overshoot. | | | | | | |
| | | | | | | | |
| **7. LULUCF emissions** | Land use and forestry (LULUCF) emissions of CO2 are based on a fixed trajectory, using outputs from the IMAGE model, based on the RCP2.6 SSP2 case. They are net CO2 emissions from deforestation, and reforestation in line with SSP2 RCP2.6 assumptions. | 2.5 | 1.2 | -1.0 | -1.5 | GtCO2 | SSP Public Database (Version 1.1) hosted by IIASA https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome . Model-Scenario: IMAGE SSP2-26 |
| | | | | | | | |
| **8. Non-CO2 GHGs** | Some non-energy sector sources of CH4 and N2O are not explicitly represented in TIAM-UCL - but rather as an emissions trajectory based on the RCP database. Such sources include CH4 from landfill and waste water, and agricuture (manure, rice paddies) and N2O from industry (nitric and adipic acid) and agriculture. In this modelling, the RCP2.6 trajectory will be used for climate ambition cases [which differs little from RCP1.9]. GWP100 values used in the model are 25 ($CH_4$) and 298 ($N_2O$). | | | | | | |
| | CH4 /N2O emissions from the energy sector (e.g. CH4 leakage from natural gas extraction and transport) are capped under an overall constraint, which includes the sources above. | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | CH4 | 275,467 | 212,033 | 178,996 | 157,291 | Kt | SR 1.5 database (Mean values from sub 2°C scenarios) |
| | N2O | 9297 | 8863 | 8320 | 7920 | Kt | SR 1.5 database (Mean values from sub 2°C scenarios) |
| | | | | | | | |
| **9. Traded commodities** | | | | | | | |
| CO2 offsets | Carbon offsets can be traded. For a globally optimal scenario, with no region specific mitigation constraints, this function is not required as the model will reduce emissions where most optimal. Where regional targets exist, trade in offsets would ensure a more optimal solution. **We do not include this feature in the analysis here.** | | | | | | |
| Energy resources | Trade is permitted for coal (HCO, BCO), oil (crude, different oil products), and gas (via LNG and pipeline). Biomass trade is for solid biomass and energy crops (primary biomass resource) and biofuels (biojet kerosene, biodiesel and bionaptha). The links for bio-trade are assumed to stay as currently. | | | | | | [26] for gas trade updates; [25] for oil trade updates |
| | | | | | | | |
| **10. Other** | | | | | | | |
| Discount rates | The social discount rate is set at 3.5%. | | | | | | |
| Base year | Model is calibrated based on 2005 IEA energy balances. Additional constraints have been introduced in the model to help represent the energy system in 2010 and 2015 - and to reflect projected emissions in 2020. A reference case is also run to generate base prices for elastic demand function. | | | | | | |

# Appendix 2: Afforestation scenario set-up

## Bioenergy set-up in TIAM-UCL

Biomass feedstocks are represented as six ‘mined’ commodities. First generation fuels are represented as bioliquids (bioethanol and biodiesel from crops which might compete with food crops for land) and biomethane (gas captured from controlled landfill sites). Primary feedstocks for second generation technologies are represented as four fractions: solid biomass, energy crops, municipal solid waste and industrial waste. Only solid biomass and energy crops can be used for BECCS in the model; the waste fractions are used directly in the residential and industrial sectors.

Solid biomass represents woody agricultural and forest residues. Availability projections are taken from the IMAGE model SSP2 baseline scenario[23]. They were derived by spatial modelling of the theoretical available potential, with the biomass fractions required for maintenance of soil quality and other uses subtracted. Cost projections are also taken from the IMAGE model SSP2 baseline scenario, derived from a review of several literature sources; cost elements include harvest, operations, storage and drying, forwarding, chipping, transport. Availability projections for dedicated energy crops are derived from the Ricardo-EE model for the UK Department for Business, Energy and Industrial Strategy [19]. This uses regional projections of abandoned agricultural land from the IMAGE model SSP2 RCP2.6 mitigation scenario and assumes no competition for land with food crops or pasture. The most degraded and water scarce land is excluded by applying constraints derived from [20]. The land considered available for bioenergy crops globally thereby totals 199 Mha in 2020, 207 Mha by 2050 and is assumed constant up to 2100. Typical yields for perennial energy crops are applied for each region and a 1.3% yearly yield increase is assumed – this figure was estimated based on an assessment of yield increases between 2010 and 2017, and a business-as-usual scenario regarding globalisation and investment [19]. The regional resources are split into 3 cost bands drawn from [28]. Land use emissions for energy crop cultivation are included in a combined Land Use Land Use Change emission coefficient. The other biomass fractions are assumed to produce no land use change. While $CO_2$ emissions from combustion are considered 0, TIAM has fixed emission coefficients for $CH_4$ and $N_2O$ emissions when biomass is used for power or liquid fuels (also contributing to GHG emissions). Carbon sequestration from BECCS is accounted for in the CCS technology. Emissions related to the biomass processing (during storage, drying and transport) are estimated at approximately 5% of the biomass carbon content.

Net $CO_2$ emissions from LULUCF (which includes deforestation, afforestation and reforestation for climate mitigation) are represented by an exogenously-fixed emissions pathway. For scenarios with no climate constraint, this is taken from the RCP8.5 scenario from its marker model MESSAGE. For 2°C and 1.5°C scenarios, it is taken from the IMAGE model for RCP2.6 mitigation scenario under SSP2. This is consistent with the representation of bioenergy crop availability, which assumes land availability with no afforestation.

## Afforestation and demand scenarios

The first scenario set explores the relative benefits of using abandoned agricultural land for bioenergy crops or afforestation. As noted by Harper et al 2018, the land carbon balance of afforestation and bioenergy crops can be compared but the fossil fuel offsets in the energy system must also be considered in order to judge the relative benefits of each. For the afforestation case, it is assumed no dedicated energy crops are grown from 2025 onwards, and instead new forest is established on the abandoned agricultural land. It is assumed residues could be extracted from these types of forestry. A single residue retrieval factor of 16 PJ/Mha/yr is assumed. This is derived from data from a typical management regime of a southern Finnish forest stand, assuming clear cutting after 70 years (EUBIA; VTT[12]). Negative emissions associated with the additional forested land are added to the exogenous land-use $CO_2$ pathway. Carbon dioxide removal rates for afforested land are derived for each geographic region from Bernal et al. (2018). It is assumed that planted forest/woodlots are established and the yearly sequestration rate is constant. Values are derived from the available data by averaging across species and humid/dry climatic conditions, and applied to each region according to its most appropriate climatic description (boreal/temperate or tropical). It is important to note that climate feedbacks on the ability of afforestation to sequester and continue to store carbon aren't considered here. With these assumptions, we model that afforested land sequesters 429 $GtCO_2$ over the period 2020-2100.

The second scenario set explores how lowering the end-use energy service demands could ease the transformation of the supply system. For the LoDem demand scenarios, the energy service demands are driven by the regional population and GDP projections for SSP1, and calibration factors are applied so that the final energy consumption falls within the plume of results from the IAMs for SSP1 [22]. The third set of tests combines SSP1 demands and negative emissions from afforestation to explore the extent to which lowering demands could trade off with the requirement for NETs in stringent climate mitigation scenarios.

In summary, for each temperature limit, the model is tested with SSP2 and SSP1 demands and an allocation of the available land to either energy crops or afforestation (Table 3). The resource potentials for each biomass fraction are summarized in Table 6.

| **Feedstock** | **Scenario** | **Global potential (EJ/y)** | | | | **Source** |
|---|---|---|---|---|---|---|
| | | **2015** | **2030** | **2050** | **2100** | |
| Bioliquids | All | 1.6 | 1.6 | 1.6 | 1.6 | TIAM-ETSAP |
| Biogas | All | 8.0 | 8.0 | 8.0 | 8.0 | |
| MSW | All | 9.9 | 12.3 | 19.1 | 20.3 | |
| Industrial | All | 2.1 | 4.4 | 7.5 | 7.5 | |
| Solid biomass | Core and Rebalanced | 40.9 | 42.6 | 44.8 | 50.0 | Based on Daioglou et al. (2016) |
| | Afforestation | 40.9 | 44.1 | 48.0 | 52.7 | Derived from Daioglou et al. (2016) and EUBIA/VTT |
| Energy crops | Core and Rebalanced | 6.4 | 17.1 | 31.4 | 31.4 | Marginal land availability and energy crop yields from Ricardo Energy & Environment (2017)<br>Supply cost curves based on Hoogwijk et al. (2009) updated based on Ricardo Energy & Environment (2017) |
| | Afforestation | 6.4 | 0 | 0 | 0 | |

**Table 6. Biomass resources in TIAM-UCL**

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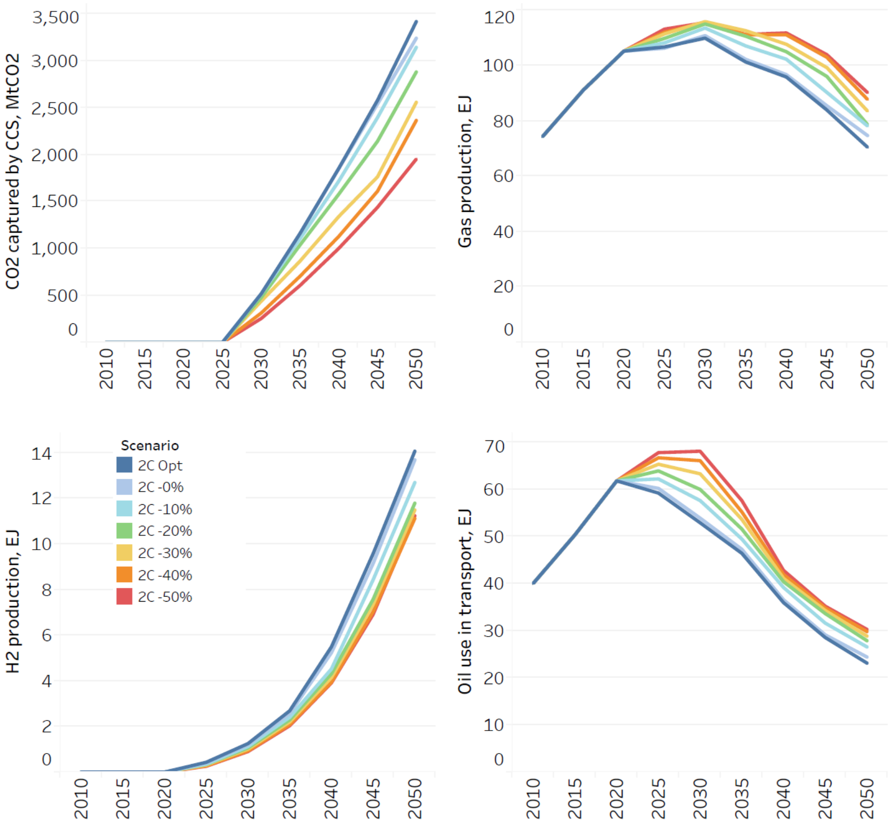
[12] VTT Wood Energy Technology Programme, Finland, http://www.eubia.org/cms/wiki-biomass/biomass-resources/challenges-related-to-biomass/recovery-of-forest-residues/

# Appendix 3: Leadership-driven scenario metrics for 2°C case

a)



b)

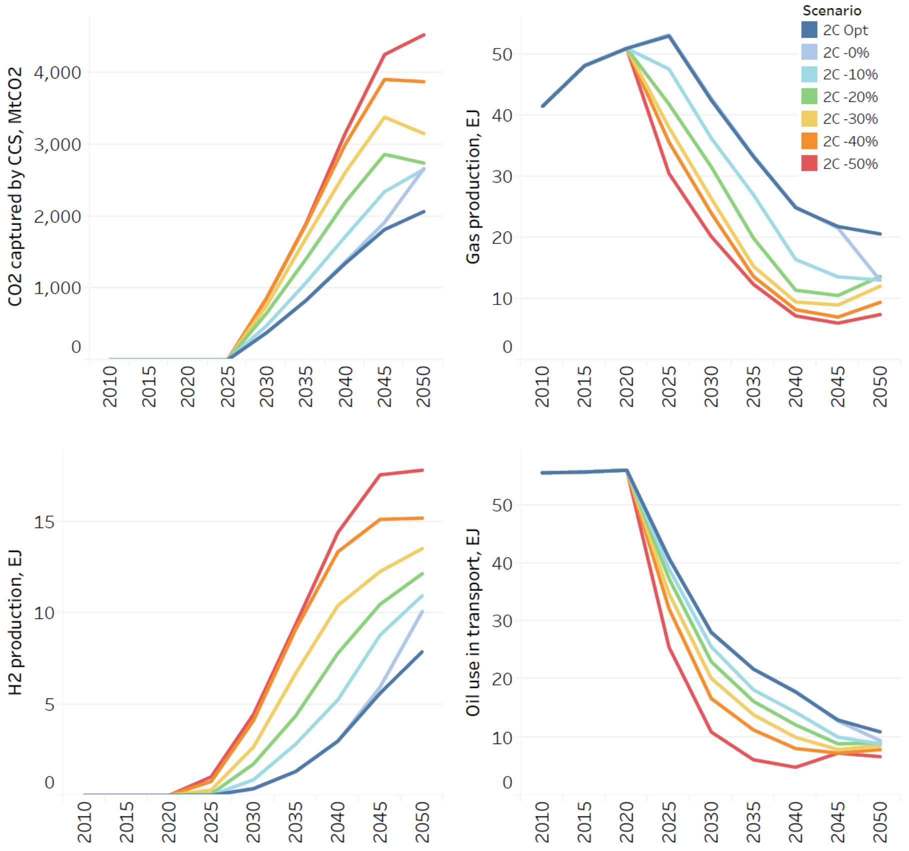


**Figure 19. Non-HAC (a) and HAC (b) group metrics under the 2°C rebalanced scenario.** All metrics are for the period 2010-50, and for both a) and b) include top-left) $CO_2$ captured by CCS; top-right) Gas production; bottom-left) H2 production; and bottom-right) oil use in transport. The Opt scenario refers to the global least-cost case, while all other scenarios meet net-zero $CO_2$ emissions in 2050, and have adjusted budgets at the levels indicated.

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